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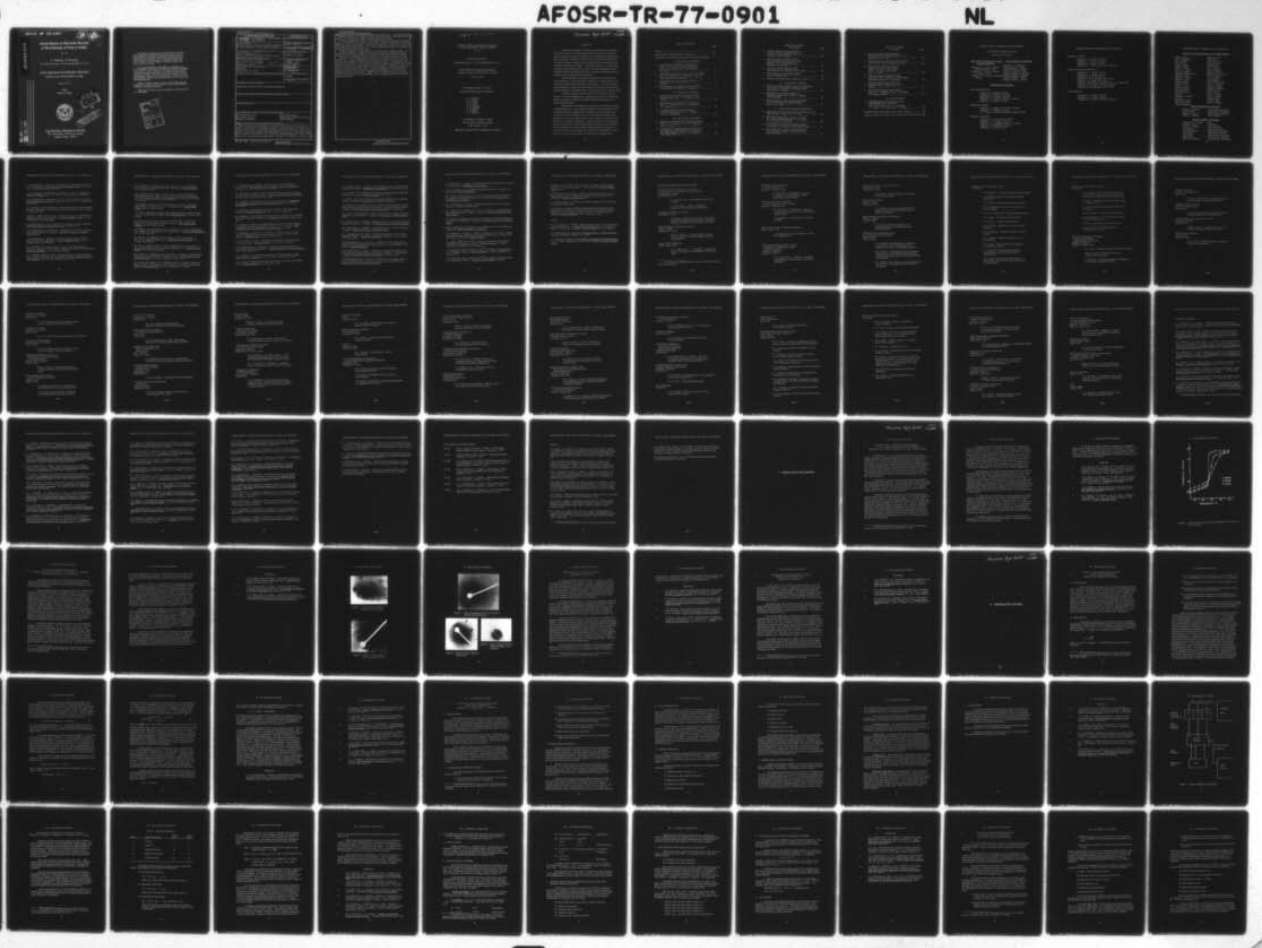

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Annual Report on Electronics Research at The University of Texas at Austin

No. 24

A Summary of Research

For the Period April 1, 1976, through March 31, 1977

JOINT SERVICES ELECTRONICS PROGRAM

Research Contract AFOSR F44620-76-C-0089

May 15, 1977

Editor

Michael F. Becker

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The research summarized in this report was supported in part by the Department of Defense's JOINT SERVICES ELECTRONICS PROGRAM (U.S. Army, U.S. Navy, and the U.S. Air Force) through the Research Contract AFOSR F44620-76-C-0089. This program is monitored by the Department of Defense's JSEP Technical Advisory Committee consisting of representatives from the U.S. Army Electronics Command, U.S. Army Research Office, Office of Naval Research and the U.S. Air Force Office of Scientific Research.

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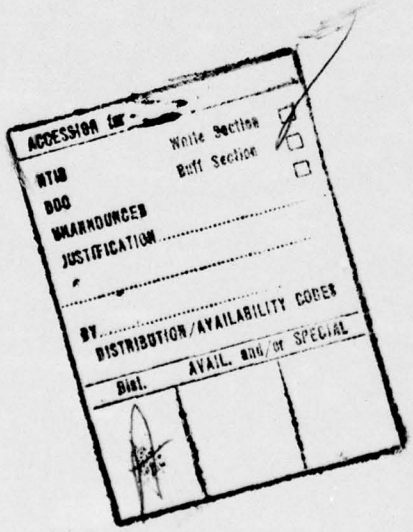

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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The investigation of computer architechture for byte string and vector operations, in the information systems area, shows iterative processing of variable length operands to be feasible. In the area of electronic computers, errors have been reduced and reliability increased with minimal redundancy, through the use of functional simulation of logic nets.

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May 15, 1977

Submitted by Edward J. Powers

for the Executive Research Committee

J. K. Aggarwal
A. A. Dougal
E. J. Powers
H. W. Smith
S. A. Szygenda
R. M. Walser
A. J. Welch
B. F. Womack

ELECTRONICS RESEARCH CENTER

The University of Texas at Austin

Austin, Texas 78712

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In this Annual Report of Electronics Research at The University of Texas at Austin, we describe recent findings, progress, and future plans in the areas of solid state electronics, information systems, electronic computers, electronic controls, plasma and quantum electronics, and radio sciences. Among the many project reports in these areas are a number of significant findings. In the solid state area, a study of the transition layers between CVD VO_2 films and oxide substrates reveals complex substrate-film interactions with significant implications for VO_2 and other material-oxide substrate systems.

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November 10-14, 1975

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Austin, Texas, 1976

A. J. Welch and P. C. Richardson, "Detection of Sleep Cycle Information Using Beat-by-Beat Heart Rate"

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(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

Third International Conference
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Austin, Texas, 1976

J. K. Aggarwal, "Computer Analysis of Color Aerial Photographs"

First American Physical Society Topical
Conference on Diagnostics of High-
Temperature Plasmas
Knoxville, Tennessee
January 7-9, 1976

E.J. Powers and T.C. Simonen, "Microwave Measurement of Plasma Density Fluctuation Amplitudes"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

Third Symposium on Computer Architecture
Clearwater, Florida
January 19-21, 1976

T.A. Welch, "An Investigation of Descriptor-Oriented Architecture"

Texas Tech University
Lubbock, Texas
February 23, 1976

E. J. Powers, "Analysis and Interpretation of Plasma Fluctuation Data Using Time Series Analysis Techniques"

Joint Institute for Laboratory Astrophysics
Boulder, Colorado
March 4, 1976

* J. W. Keto, "Reactions Important to the Production and Loss of Excited Argon and Xenon Molecules"

Thirteenth Annual Electronics Review
The University of Texas at Austin
Austin, Texas
March 9, 1976

* F. X. Bostick, "An Experiment to Measure the Character of ULF Wave Propagation in the Oceanic Crust West of the Olympic Peninsula"

* F.X. Bostick, "Transmitting Antenna Performance Evaluations for Project Sanguine/Seafarer Site Surveys Using Magnetotelluric Tensor Impedances Measurements"

* E.L. Hixson, "Low-Frequency, Deep-Submergence, Fluid Acoustic Transducers and End-Fire Array Microphone"

Thirteenth Annual Electronics Review
(continued)

* J.K. Aggarwal, "Electronic Digital Signal Processing"

* T.J. Wagner, "Electronic and Optical Pattern Recognition"

* S.I. Marcus, "Stochastic Nonlinear Estimation"

* T.K.M. Agerwala, "Studies of Concurrent Computing Systems"

* R. T. Yeh, "Electronic Computer Software Systems"

* R. H. Flake, "Electronic Control Systems"

* T.A. Welch, "Computer System Design"

* S.A. Szygenda, "Electronic Computer Software Systems"

* E.W. Thompson, "Electronic Computer Software Systems"

* A.B. Buckman, "Refractive Changes in PbI_2 by Photolysis"

* R.W. Bené, "Solid-Solid Surface Reactions in In/Se Binary System"

* A.J. Syllaios, "Compositional Profiling of Interfaces with Glow Discharge Optical Spectroscopy"

* E.J. Powers, "Analysis and Interpretation of Plasma Fluctuation Data Utilizing Digital Time Series Analysis"

Thirteenth Annual Electronics Review
(continued)

* M.F. Becker, "Third Harmonic Generation in SF_6 at 10.6 Microns" and "Picosecond Optical Measurement of Ultrafast Physical Phenomena"

* J. Knopp, "Multichannel Image Decoding Using a Composite Filter"

* M. Fink, "Electron Diffraction from Atoms and Molecules"

* W.W. Robertson, "Molecular Gas Dynamics"

* L.W. Frommhold, "Laser-Raman Spectroscopy of Monoatomic Gases"

* J. Keto, "High-Energy Gas Laser Systems"

* B.F. Womack, "Desensitized Specific Optimal System Design"

The 1976 Conference on Information Sciences and Systems
The Johns Hopkins University
Baltimore, Maryland
March 31 - April 2, 1976

G. L. Wise, "Spectral Densities of Markov Processes"

Steven I. Marcus, "Analysis of Poisson-Driven Bilinear Systems"

* T. Agerwala, "Timing and Priority Considerations in Concurrent Computing Systems"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

Brandeis University
Waltham, Massachusetts
April, 1976

* M. Fink, "Relativistic and Correlation Effects in Atoms Studied by Electron Scattering"

Carnegie-Mellon University
Pittsburgh, Pennsylvania
April 8, 1976

* M. Fink, "Relativistic and Correlation Effects in Atoms Studied by Electron Scattering"

Invited Speaker at the University of Florida
Gainesville, Florida
April 8-9, 1976

Steven I. Marcus, "Algebraic Structure and Finite Dimensional Nonlinear Estimation"

IEEE Region V Conference
Austin, Texas
April 14-16, 1976

R.H. Flake, "Qualitative Theory in Estuarine Water Quality Modelling"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

The University of Texas at Austin
April 21, 1976

* M. Fink, "Relativistic and Correlation Effects in Atoms Studied by Electron Scattering"

Electrical Engineering Visiting Committee
Houston, Texas
May 10, 1976

M. F. Becker, "Research Report: Nonlinear Optics and Lasers"

1976 IEEE International Conference
on Plasma Science
The University of Texas at Austin
Austin, Texas
May 24-26, 1976

* E.J. Powers and Y.C. Kim, "Application of Digital Spectral Analysis Techniques to the Diagnostic Problem of Fluctuation-Induced Transport"

E.J. Powers, W.C. Turner, and T.C. Simonen, "Simultaneous Enhancement of Ion Velocity Space Diffusion and Ion Cyclotron Oscillations in a Mirror Confined Plasma"

* E.J. Powers and Y.C. Kim, "Bispectral Wave Analysis of Nonlinear Wave-Wave Interactions in Plasmas"

University of Sterling
Sterling, U.K.
May 25, 1976

* M. Fink, "Relativistic and Correlation Effects in Atoms Studied by Electron Scattering"

University of Saint Andrews
Saint Andrews, U.K.
May 28, 1976

* M. Fink, "Charge Density Distributions of Molecules"

University of Manchester
Institute of Science and Technology
Manchester, U.K.
June 1, 1976

* M. Fink, "Structure Determination by Electron Scattering and Counting Machines"

University of Reading
Reading, U.K.
June 3, 1976

* M. Fink, "Charge Density Distributions of Molecules"

IX International Quantum Electronics Conference
Amsterdam, The Netherlands
June 14-18, 1976

* M. F. Becker, "Third Harmonic Generation at 10.6 Microns"

International Federation of Automatic Control Symposium on Large Scale Systems Theory and Applications
Udine, Italy
June 16-20, 1976

* B.J. Olufeagba, R.H. Flake, and K.J. Almquist, "A Multiple Shooting and Sweep Algorithm for Optimal Point Controlled Distributed Parameter Systems"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

University of Bielefeld
Bielefeld, W. Germany
June 17, 1976

* M. Fink, "Relativistic and Correlation Effects in Atoms Studied by Electron Scattering"

University of Muenster
Muenster, W. Germany
June 23, 1976

* M. Fink, "Charge Density Distributions of Molecules"

University of Kaiserslautern
Kaiserslautern, W. Germany
June 30, 1976

* M. Fink, "Relativistic and Correlation Effects in Atoms Studied by Electron Scattering"

NASA Seminar/Research Institute on
Differential and Algebraic Geometry
for Control Engineers
Moffett Field, California
June 30, 1976

* Steven I. Marcus, "Modeling and Stability of Linear Systems with Multiplicative Poisson Noise"

Gordon Research Conference on
Lasers in Medicine and Biology
Meriden, N.H.
July 5-9, 1976

A.J. Welch and Les Priebe, "Prediction of Retinal Thermal Injury from Laser Radiation"

A.J. Welch and Mike Mandell, "Receptive Field Measurements After Laser Radiation"

University of Tuebingen
Tuebingen, W. Germany
July 20, 1976

*M. Fink, "Structure Determination by Electron Scattering and Counting Machines"

13th International Conference on the Physics of Semiconductors,
Rome, Italy
August, 1976

*R. M. Walser and R.W. Bené, "Solid Phase Reactions at Transition Metal-Silicon Interfaces"

Symposium on the Nature and Physical Properties of the Earth's Crust
Vail, Colorado
August 2-6, 1976

*F.X. Bostick and H.W. Smith, "Magnetotelluric and Dipole-Dipole Soundings in Northern Wisconsin"

13th IEEE Computer Society International Conference
Mayflower Hotel
Washington, D.C.
September 1976

T.K.M. Agerwala, "Designing with Microprocessors"

Division Meeting of Optical Society of America
Houston, Texas
September 8, 1976

*J.W. Keto, "Kinetic Studies of Excimer Lasers Using Single Photon Timing"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

Rice University
Houston, Texas
September 28, 1976

* Steven I. Marcus, "The Use of Harmonic Analysis in Suboptimal Estimator Design"

The 1976 International
Telemetering Conference
Los Angeles, California
September 28-30, 1976

G.L. Wise and J.B. Thomas, "Zero Memory Nonlinear Transformations of Gaussian Processes"

Fourteenth Annual Allerton Conference
on Circuit and System Theory
Monticello, Illinois
September 29 - October 1, 1976

N.C. Gallagher, J.W. Allen, and G.L. Wise, "Fourier Series Representation for Polynomials with Application to Nonlinear Digital Filtering"

G. L. Wise and N.C. Gallagher, "A Representation for Spherically Invariant Random Processes"

International Conference on
Software Engineering
San Francisco, California
October 1976

E. W. Thompson, "A Data Structure and Drive Mechanism for a Table-Driven Simulation System Employing Multilevel Structured Representations of Digital Systems"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

Euromicro Symposium
Venice
October 12, 1976

G. J. Lipovski, "The Architecture of a Simple Effective Control Processor"

EPA University Noise Seminar
Purdue University
October 18-20, 1976

E. L. Hixson, "Vehicle Noise Source Level Measuring System"

ACM '77
Houston, Texas
October 20, 1976

G. J. Lipovski, "Panel Session: *Micros-Minis-Maxis*"

U.S. Geological Survey Workshop on
Electrical Methods in Geothermal Exploration
Snowbird, Utah
November 4-7, 1976

*H.W. Smith, "Real Time, On-Site Processing of Magnetotelluric Data"

F.X. Bostick, "A Simple Almost Exact Method of MT Analysis"

F.X. Bostick, "The Effect of Lateral Inhomogeneities in a Magnetotelluric Survey"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

Chemical Engineering Department
The University of Texas at Austin
Austin, Texas
November 9, 1976

* Steven I. Marcus, "The Use of Harmonic Analysis in Suboptimal Estimator Design"

IEEE International Symposium on
Pattern Recognition
San Diego, California
November 9-11, 1976

* T. J. Wagner, "A Distribution-Free *Performance Bound in Error Estimation*"

The American Physical Society Division of
Plasma Physics Meeting
San Francisco, California
November 15-19, 1976

* Y. C. Kim and E. J. Powers, "Utilization of Bispectral Analysis in Experimental Studies of Nonlinear Wave-Wave Interactions"

E.J. Powers, et al., "Fluctuation Spectrum in the NASA Lewis Bumpy Torus"

Surface Science Seminar
Bell Telephone Labs
Murray Hill, New Jersey
December 1976

* R.W. Bené and R.M. Walser, "Schottky Barriers at Transition-Metal-Silicon Interfaces"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

Surface Physics Seminar
Bell Telephone Labs
Murray Hill, New Jersey
December 1976

* R. M. Walser and R.W. Benē, "Nucleation of Silicides at Transition Metal-Silicon Interfaces"

IEEE Conference on Decision and Control
Clearwater Beach, Florida
December 1-3, 1976

* Steven I. Marcus, "The Use of Spherical Harmonics in Suboptimal Estimator Design"

Fall Annual Meeting
American Geophysical Union
San Francisco, California
December 6-10, 1976

F.X. Bostick, H.W. Smith and J.E. Boehl, "Magnetotelluric Measurement over Kilauea Iki Lava Lake"

Second International Conference and
Winter School on Submillimeter Waves
and Their Applications
San Juan, Puerto Rico
December 6-11, 1976

A. B. Buckman, "Theory of an Efficient Electronic Phase Shifter Employing a Multilayer Dielectric-Waveguide Structure"

1977 IEEE International Symposium
on Circuits and Systems
Phoenix, Arizona, 1977

H. Chang and J. K. Aggarwal, "Design and Simulation of Two-Dimensional Interpolated Filter Systems"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

10th International Hawaii Conference
on System Sciences
January 6-7, 1977

* T.K.M. Agerwala and B. Lint, "A Comparison of Synchronizing Primitives"

University of Alberta
January 23, 1977

G. J. Lipovski, "On Virtual Memories and Microprocessors"

4th Annual Conference on
The Physics of Compound
Semiconductor Interfaces
Princeton, New Jersey
February 1977

* R. W. Bené and R.M. Walser, "The Effect of a Glassy Membrane on the Schottky Barrier Between Silicon and Metallic Silicides"

Solid Phase Epitaxy Program Review
California Institute of Technology
Pasadena, California
March 1977

R. M. Walser, "Recrystallization of Ion-Implanted Amorphous Silicon Layers"

R. W. Bené, "Silicide-Silicon Barriers"

Intel Corporation
March 1977

R. M. Walser, "Electronic Conduction in Ion-Implanted Poly Silicon"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

INTER-NOISE 77
Zurich, Switzerland
March 1977

E. L. Hixson, "The Qualifications for a Noise Control Engineer"

14th Annual Electronics Research Review
The University of Texas at Austin
Austin, Texas
March 8-9, 1977

* H. W. Smith, Overview of "Modeling Subsurface Resistivities with Magnetotelluric Data (MT Data)"

* B. F. Womack, Overview of "Electronic Control Systems"

* S. I. Marcus, "The Use of Harmonic Analysis in Sub-Optimal Estimator Design"

G. L. Wise, "An Overview of Some Recent Results in Communication and Control"

* J. K. Aggarwal, "Recent Results on Two-Dimensional Signal Processing"

* T. J. Wagner, "Recent Results on Nonparametric Estimation and Discrimination"

* S.A. Szygenda, Overview of "Electronic Computer Software System" and "Electronic Computer Design and Analysis"

G. J. Lipovski, "Computer Architecture and Microprocessor Systems"

* T. K. M. Agerwala, "Studies in Concurrent Computer Systems"

14th Annual Electronics Research Review
(continued)

* E. W. Thompson, "Validation of Hardware, Software Systems"

* R. T. Yeh, "Software System Design Methodology"

* R. M. Walser, Overview of "Basic Solid State Materials Research", and "Research on Solid State Infrared and Optical Devices"

* R. W. Bené, "Schottky Barriers in Transition Metal-Silicon Systems"

* A. B. Buckman, "Photolysis in PbI_2"

* R. M. Walser, "Recrystallization of Ion-Implanted Amorphous Silicon"

* E. J. Powers, Overview of "Atomic and Molecular Electronic Processes," "Laser, Holographic, and Optical Systems," "Linear and Nonlinear Wave Phenomena in Optics and Plasmas," and "High Energy Gas Laser Systems"

* M. Fink, "Electron Scattering from Atoms and Molecules"

* M.F. Becker, "Infrared Nonlinear Optics in Molecular Gases"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

1977 March Meeting of the
Applied Physics Society
San Diego, California
March 21-24, 1977

* M. Fink, "Can Electron Diffraction Provide More Accurate Molecular Charge Densities Than Current Theories"

Fourth Symposium on Computer Architecture
Silver Spring, Maryland
March 23-25, 1977

T.A. Welch and H.L. Tredennick, "High-Speed Buffering for Variable Length Operands"

Symposium on Computer Architecture
Washington, D.C.
March 24, 1977

G.J. Lipovski, "Panel Session: Buzz-words in Computer Architecture," and "On Virtual Memories and Micronetworks"

The Johns Hopkins Conference on
Information Sciences and Systems
Baltimore, Maryland
March 30 - April 1, 1977

* Steven I. Marcus, "Modeling and Analysis of Poisson Driven Markov Processes"

Colloquium on Decision and Control
University of Texas at Austin
Austin, Texas
March 30, 1977

B.F. Womack, "Design and Control of Feedback Systems via Sensitivity Theory"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS)

The 1977 Conference on
Information Sciences and Systems
The Johns Hopkins University
Baltimore, Maryland
March 30 - April 1, 1977

G.L. Wise and N.C. Gallagher, "A Novel Approach for the Computation of Chebyshev Polynomial Expansions"

University of Illinois
Chicago Circle Campus
April 17, 1977

R.T. Yeh, "An Outline of a Design Methodology for Data Base Systems"

Joint Services Topical Review on Informational
Aspects of Decision and Control
Cambridge, Massachusetts
May 4-5, 1977

* Steven I. Marcus, "The Use of Spherical Harmonics in Suboptimal Esitmator Design"

Syracuse, New York
May 17, 1977

G. J. Lipovski, "On Imaginary Fields, Token Transfers, and Floating Codes in Intelligent Secondary Memories"

NCC
Dallas, Texas
June 16, 1977

G. J. Lipovski, "An Organization for Optical Links Between Integrated Circuits"

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

PUBLISHED ABSTRACTS

E. J. Powers and T.C. Simonen, "Microwave Measurement of Plasma Density Fluctuation Amplitudes," Bulletin of the American Physical Society, Vol. 21, No. 5, 1976, p. 855.

* E. J. Powers and Y. C. Kim, "Application of Digital Spectral Analysis Techniques to the Diagnostic Problem of Fluctuation-Induced Transport," Conference Record - The 1976 IEEE International Conference on Plasma Science, IEEE Catalog No. 76CH1083-5-NPS, p. 47.

E. J. Powers, W. C. Turner, and T. C. Simonen, "Simultaneous Enhancement of Ion Velocity Space Diffusion and Ion Cyclotron Oscillations in a Mirror Confined Plasma," Conference Record - The 1976 IEEE International Conference on Plasma Science, IEEE Catalog No. 76CH1083-5-NPS, p. 77.

* E. J. Powers and Y. C. Kim, "Bispectral Wave Analysis of Nonlinear Wave-Wave Interactions in Plasmas," Conference Record - The 1976 IEEE International Conference on Plasma Science, IEEE Catalog No. 76CH1083-5-NPS, p. 78.

E. J. Powers, et al, "Fluctuation Spectra in the NASA Lewis Bumpy Torus", Bulletin of the American Physical Society, Vol. 21, 1976, p. 1069.

* Y. C. Kim and E. J. Powers, "Utilization of Bispectral Analysis in Experimental Studies of Nonlinear Wave-Wave Interactions," Bulletin of the American Physical Society, Vol. 21, 1976, p. 1081.

S. I. Marcus, "Estimation and Analysis of Nonlinear Stochastic Systems," IEEE Transactions on Information Theory, Vol. IT-22, July 1976, p. 503.

* A. B. Buckman, "Theory of an Efficient Electronic Phase Shifter Employing a Multilayer Dielectric-Waveguide Structure," IEEE Conference Records - Abstracts, Second International Conference and Winter School on Submillimeter Waves and Their Applications, IEEE Catalog No. 76-CH-1152-8-MTT, San Juan, Puerto Rico, December 6-11, 1976.

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*Funded entirely or in part by the Joint Services Electronics Program.

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

* M. Fink, "Can Electron Diffraction Provide More Accurate Charge Densities Than Current Theories," Bulletin of The American Physical Society, Vol. 22, 1977, p. 306.

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

CONFERENCE PROCEEDINGS

* R. T. Yeh and C. Reynolds, "Verification of Nondeterministic Programs," Proceedings of the 11th Asimolar Conference on Circuits, Systems, and Computers, November 1975.

* T. A. Welch, "An Investigation of Descriptor Oriented Architecture," Proceedings of the Third Symposium on Computer Architecture, Clearwater, Florida, January 19-21, 1976, Cat. No. 76CH1043-5C, pp. 141-146.

* T. K.M. Agerwala, "Timing and Priority Considerations in Concurrent Computer Systems," Proceedings of the Conference on Information Sciences and Systems, The Johns Hopkins University, Baltimore, Maryland, March 31 - April 2, 1976.

G. L. Wise, "Spectral Densities of Markov Processes," Proceedings of the 1976 Conference on Information Sciences and Systems, The Johns Hopkins University, March 31 - April 2, 1976, p. 161.

* R. T. Yeh, "Prospectives on the Nature of Software Problems,"Proceedings of the IFIP Working Conference, Tokyo, Japan, April, 1976.

* S. I. Marcus, "Analysis of Poisson Driven Bilinear Systems," Proceedings of the 1976 Conference on Information Sciences and Systems," The Johns Hopkins University, April 1976, pp. 411-415.

* A. B. Buckman,ed., "1976 Region V IEEE Conference Digest," IEEE Catalog No. 76CH1068-6-REG5, Austin, Texas, April 14-16, 1976.

R. H. Flake, "Qualitative Theory in Estuarine Water Quality Modelling," Proceedings of the IEEE Region V Conference, Austin, Texas, April 14-16, 1976.

* R. T. Yeh, "An Approached Program Verification," Proceedings of the Design Automation Workshop, San Francisco, California, June, 1976.

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*Funded entirely or in part by the Joint Services Electronics Program.

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* S. I. Marcus, "Modeling and Analysis of Linear Systems Driven By Multiplicative Poisson White Noise," Proceedings of the NASA Seminar/Research Institute on Differential and Algebraic Geometry for Control Engineers, June 1976.

* B. J. Olufeagba, R. H. Flake, and K. J. Almquist, "A Multiple Shooting and Sweep Algorithm for Optimal Point Controlled Distributed Parameter Systems," Proceedings of the International Federation of Automatic Control Symposium on Large Scale Systems Theory and Applications, ed., G. Guardabassi and A. Locatelli, Udine, Italy, June 16-20, 1976.

* R. M. Walser and R. W. Bené, "Solid Phase Reactions at Transition Metal-Silicon Interfaces," Proceedings of the International Conference on Physics of Semiconductors, Rome, Italy, August 1976.

G. L. Wise, "A Comment on the Estimation of Probability Density Functions," to appear in Proceedings of the Workshop on Decision Information for Tactical Command and Control, Airlie, Virginia, September 22-25, 1976.

G. L. Wise and J. B. Thomas, "Zero Memory Nonlinear Transformations of Gaussian Processes," (invited paper), Proceedings of the 1976 International Telemetering Conference, Los Angeles, California, September 28-30, 1976, pp. 136-142.

N. C. Gallagher, J. W. Allen, and G. L. Wise, "Fourier Series Representation for Polynomials with Application to Nonlinear Digital Filtering," Proceedings of the Fourteenth Annual Allerton Conference on Circuit and System Theory, Monticello, Illinois, September 29-October 1, 1976, pp. 211-218.

G. L. Wise and N. C. Gallagher, "A Representation for Spherically Invariant Random Processes," Proceedings of the Fourteenth Annual Allerton Conference on Circuit and System Theory, Monticello, Illinois, September 29 - October 1, 1976, pp. 460-469.

* S. A. Szygenda, N. Billawala, and E. W. Thompson, "A Data Structure and Drive Mechanism for a Table-Driven Simulation System Employing Multilevel Structural Representations of Digital Systems," Proceedings of the International Conference on Software Engineering, October 1976.

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* T. J. Wagner, "A Distribution-Free Performance Bound in Error Estimation," Proceedings of the IEEE International Symposium on Pattern Recognition, San Diego, California, November 9 - 11, 1976.

* S. I. Marcus and A. S. Willsky, "The Use of Spherical Harmonics in Suboptimal Estimator Design," Proceedings of the 1976 IEEE Conference on Decision and Control, December 1976, pp. 189-203.

* B. F. Womack and D. O. Nilsson, "Generalized Tensorial Systems Analysis," 1976 Region V IEEE Conference Digest, Library of Congress Cat. No. 72-87449, pp. 315-317.

B. F. Womack and C. R. Browning, "Shift Patterns in Heuristic Searches," 1976 Region V IEEE Conference Digest, Library of Congress, Cat. No. 72-97449, pp. 309-314.

P. C. Richardson and A. J. Welch, "Detection of Sleep Cycle Information Using Beat-by-Beat Heart Rate," 1976 Region V IEEE Conference Digest, Library of Congress Cat. No. 76CH1068-6, pp. 203-207.

* W. G. Gipe and T. A. Welch, "Processor Design for Data Structure Handling in Data Management Systems," 1976 Region V IEEE Conference Digest, Cat. No. 76CH1068-6, pp. 241-246.

* H. L. Tredennick and T. A. Welch, "An Operand Address Generator for a Variable Word Length Processor," 1976 Region V IEEE Conference Digest, Cat. No. 76CH1068-6, pp. 247-252.

* T. A. Welch, "A Computer Architecture for Support of High-Level Languages," 1976 Region V IEEE Conference Digest, Cat. No. 76CH1068-6, pp. 253-256.

* J. J. Montemayor and B. F. Womack, "More on the Conjecture by Siljak," 1976 Region V IEEE Conference Digest, Cat. No. 76CH1068-6, pp. 318-320.

B. F. Womack, T. Nagooka, and M. Oda, "Concept Formation of Multimodal Hill in Heuristic Search Behavior," Proceedings, 1976 Joint Automatic Control Conference, 10pp.

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F. X. Bostick, "A Simple Almost Exact Method of MT Analysis," Proceedings of the U.S. Geological Survey Workshop on Electrical Methods in Geothermal Exploration, University of Utah, January, 1977.

* T. K. M. Agerwala and B. Lint, "A Comparison of Synchronizing Primitives," Proceedings of the 10th International Hawaii Conference on System Sciences, January 6-7, 1977.

* E.L. Hixson, "The Qualifications for a Noise Control Engineer," Proceedings, INTER-NOISE 77, ed. Eric J. Rothe, PB-6, March 1-3, 1977.

* T. A. Welch and H. L. Tredennick, "High-Speed Buffering for Variable Length Operands," Proceedings of the Fourth Symposium on Computer Architecture, Silver Spring, Maryland, March 23-25, 1977, Cat. No. 77CH1182-5C, pp. 205-210.

G. L. Wise and N. C. Gallagher, "A Novel Approach for the Computation of Chebyshev Polynomial Expansions," to appear in Proceedings of the 1977 Conference on Information Sciences and Systems, The Johns Hopkins University, March 30-April 1, 1977.

* S. A. Szygenda, "The Evolution of Functional Simulation from Gate Level Simulation," 1977 IEEE International Symposium on Circuits and Systems Proceedings, April 1977.

* Ajoy K. Bose and S. A. Szygenda, "Detection of Static and Dynamic Hazards in Logic Nets," to be presented at the 14th Design Automation Conference in New Orleans, June 1977.

* Ajoy K. Bose and S. A. Szygenda, "Design of a Diagnosable and Fault Tolerant Input/Output Controller," to be presented at the National Computer Conference in Dallas, June 1977.

* T. K. M. Agerwala, "Communication, Computation, and Computer Architecture," Record of 1977 International Communication Conference, Chicago, June 1977.

* S. I. Marcus and A. S. Willsky, "Estimation on Compact Lie Groups," to appear in Proceedings of the 1977 Joint Automatic Control Conference, San Francisco, California, July 1977.

(PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS)

* B. F. Womack and V. M. Levykin, "Circular-Polar Configurations of Dynamic Multiple-Connected Subsystems," a paper accepted for the IFAC Symposium on Information Control Problems in Manufacturing Technology, Tokyo, Japan, October 17-20, 1977, 11 pp.

* S. I. Marcus, "Modeling and Analysis of Poisson Driven Markov Processes," to appear in Proceedings of the 1977 Conference on Information Sciences and Systems, The Johns Hopkins University, 1977.

* K. Kohanbash and S. I. Marcus, "Fourier Series and Estimation: An Application to Optical Phase Tracking," submitted to the 1977 IEEE Conference on Decision and Control.

* R. B. Asher and S. I. Marcus, "Optimal and Suboptimal Estimation with Mixed Rotational Observables," submitted to the 1977 IEEE Conference on Decision and Control.

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FULL LENGTH TECHNICAL REPORTS

TR 176 Troy F. Henson and Baxter F. Womack, "Desensitized Specific Optimal System Design," December 1, 1975.

TR 178 Jerome Knopp and Elmer L. Hixson, "Multichannel Image Decoding," January 15, 1976.

TR 180 L. A. Priebe and A. J. Welch, "The Measurement of Threshold Temperatures in the Ocular Fundus for Laser Induced Visible Lesions," February 1, 1976.

TR 181 M. T. Manry and J. K. Aggarwal, "The Design of Multidimensional FIR Digital Filters by Phase Correction," August 12, 1976.

TR 182 C. S. Penrod and T. J. Wagner, "Nonparametric Estimation With Local Rules," October 11, 1976.

TR 183 L. P. Devroye and T. J. Wagner, "Nonparametric Discrimination and Density Estimation," December 1, 1976.

TR 184 W. N. Martin and J. K. Aggarwal, "Dynamic Scene Analysis The Study of Moving Images," January 15, 1977.

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REPORTS

A.J. Welch, L.A. Priebe, G.D. Polhamus, and G.D. Mistry, "Model of Thermal Injury Based on Temperature Rise in Fundus Exposed to Laser Radiation," Final Report for Brooks Air Force Base Contract F41609-74-C-0025, Electronics Research Center, The University of Texas at Austin, 1975.

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I. SOLID STATE ELECTRONICS

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(I. SOLID STATE ELECTRONICS)

A. INVESTIGATION OF TRANSITION LAYERS BETWEEN CVD-VO_2 THIN FILMS AND OXIDE SUBSTRATES †

Professor R. M. Walser, Professor R. W. Bené, and Ron Remke

Our research on VO_2 thin films was initiated as a model system in which to address fundamental questions about the behavior of electronic devices operating at steady states far from thermodynamic equilibrium. In VO_2 thin film resistors the dissipative structure is a high current filament with an abrupt metal-semiconductor phase boundary. Our previous investigations of the switching [1] and bolometric response [2] of these filaments revealed several anomalies indicating that the phase boundary was pinned for small thermal perturbations. Phase boundary pinning is expected to significantly alter the interpretation of the many previous studies of electronic and optical properties of VO_2 thin films and devices [3].

Our research in the past year has been directed toward determining the origin of this pinning. The results obtained conclusively show that the observed pinning is due to an interfacial layer between the chemically deposited VO_2 films and the oxide substrates, i.e., sapphire (Al_2O_3) and quartz (SiO_2). Our findings and their interpretations are summarized in a forthcoming journal article [4].

Concentration profiles obtained from AES analysis show that substrate metal atoms (Al from sapphire and Si from quartz) penetrate the VO_2 film a distance 1000Å from the interface. The large depth of inter-diffusion is surprising considering the stability of the bulk metal-oxide bonds of these systems and the low ($500^{\circ}C$) reaction temperature. Similar low temperature interfacial reactions are, however, commonly observed at metal-semiconductor interfaces. Because the $68^{\circ}C$ metal-semiconductor phase transition is sensitive to small concentrations of metal impurity atoms, but relatively insensitive to stress, one can determine the electronic properties of both transition regions by comparing the measured temperature dependence of the VO_2 film resistance as a function of film thickness.

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†This research was supported entirely by the Joint Services Electronics Program under Contract F44620-76-C-0089.

In summary, the AES data show that while both systems have chemical transition regions, the interface of VO_2-Al_2O_3 is electrically inactive compared with that of VO_2-SiO_2. The data shows that the transition temperature of the first system is identical to bulk VO_2 and independent of film thickness while that of the latter varies as shown in Fig. 1. The electrical inactivity of the VO_2-Al_2O_3 implies that Al must be segregated during the crystallization of VO_2 and that the transition region has a much lower conductance than that of semiconducting VO_2. The opposite is true for the VO_2-SiO_2 interface; Si is evidently incorporated in the VO_2 crystalline grains and the interfacial region has a conductance comparable with VO_2 and a higher transition temperature.

The existence of the transition region has serious implications for understanding switching and phase boundary dynamics in VO_2 structures with film thicknesses comparable with the transition region. For example, in VO_2-SiO_2, the dominant conduction path before thermal switching will be along the transition region, shifting to the surface after the switch occurs. Thus, the nucleation of the phase boundary will be thermally driven by the subsurface region, but the easy growth path of the filament will be along the surface. Clearly the switching dynamics of the phase boundary in this system will be quite different than those of the VO_2-Al_2O_3 system where filament nucleation and growth should both occur on the surface.

To further test our hypothesis on impurity segregation in these systems, thin deposited films of Al and Si were diffused into the as-deposited amorphous VO_x film and into polycrystalline V_2O_5 after oxidation-crystallization of the a-VO_x. From the shift in T_t relative to that of the bulk crystal, we conclude that neither Al or Si can diffuse into crystalline V_2O_5 or VO_2 at 500°C, but both are incorporated into the crystalline phase if present in the amorphous phase. This implies that the Al in the AES profile of VO_2-Al_2O_3 was not in the metallic state during the reaction cycle.

In principle, the existence of a transition layer provides an explanation for the anomalies we observed earlier. These are discussed in more detail in our forthcoming paper.

In summary, we expect to detect a transition from interface-dominated to surface-dominated effects in relatively thick (>>500 Å) VO_2 films on SiO_2 substrates at high bias levels. This transition is shown in Fig. 2 for the bias-dependent black-body radiance profiles of the filament and in Fig. 3 for the bias dependence of the spatial profiles of the bolometric response of the filament.

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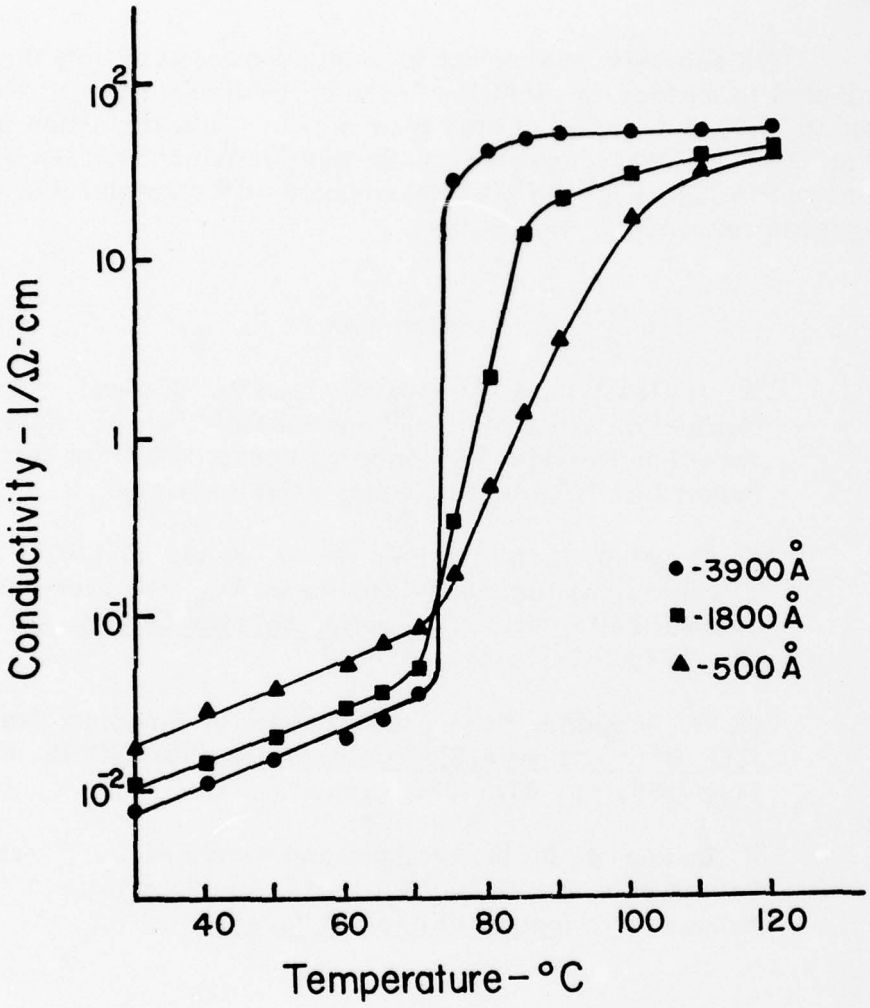


Figure 1. Conductivity Transition (versus temperature) For Three VO_2 Films on Quartz.

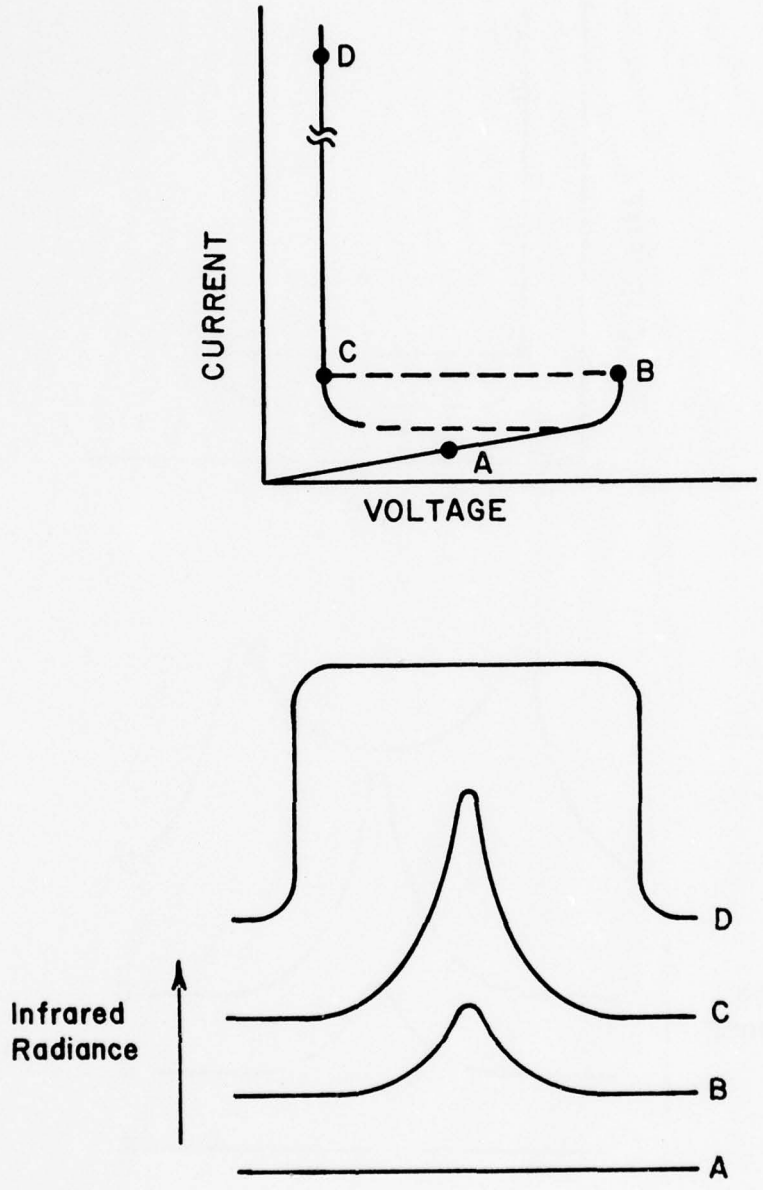
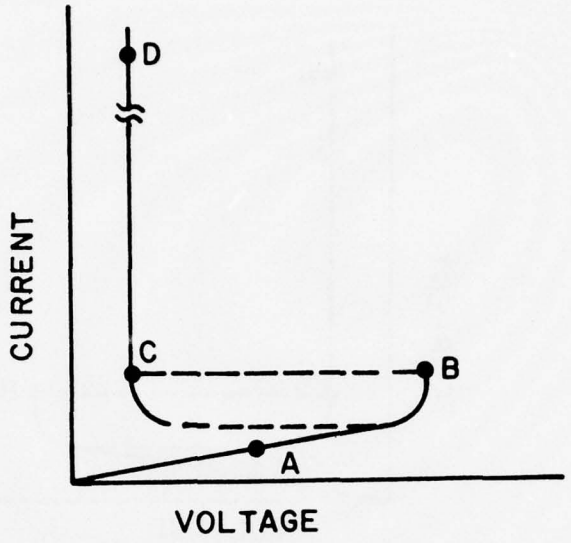


Figure 2. Spatial Infrared Radiance Profiles Of The Filament As A Function Of Bias.



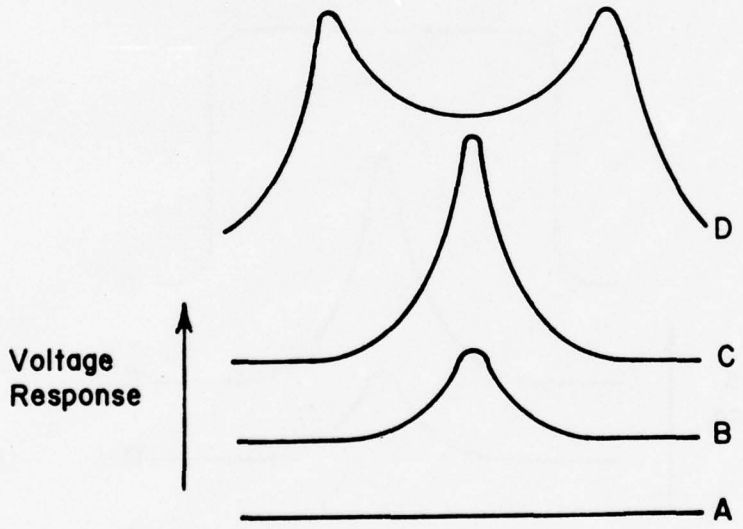


Figure 3. Spatial Profiles Of Bolometric Response Of The Filament As A Function Of Bias.

B. SOLID-SOLID INTERFACE REACTIONS †

Professor R. W. Benê, Professor R. M. Walser, W. J. Schaffer, James Hu, Mark Chonko, and Dan Richter

The purpose of this work is to determine the relationship of thermodynamic equilibrium parameters to interphase reactions in thin films at low temperatures, where it appears that the new phases formed are determined kinetically.

Based upon experiments on compound nucleation, surface reconstruction, Schottky barrier heights, recrystallization, etc., we have postulated a model [1, 2, 3] for the dynamics of phase formation in Si-metal and Ge-metal systems. A prominent feature of this model is a predicted glassy membrane region between crystalline phases. These glass-like interphases are expected to significantly affect the kinetics of thin film phase formation, diffusion, and the static properties, such as Schottky barrier heights, in metal-semiconductor systems. In an attempt to verify the existence of these membrane regions and also to study the phase nucleation in thin films in more detail concerning parameter variations, we have begun measurements on systems of thin metals (5-1000 Å) sputtered onto single crystal silicon substrates. The measurements we are doing at present are x-ray diffraction and transmission electron diffraction (TED), and will be expanded to include Auger spectroscopy and Schottky barrier measurements in the near future.

Transmission electron diffraction measurements are presently underway on thin metal films of Pd, Pt, Ni and Co on (100) Si. We are doing two types of experiments: one is to deposit films ranging from ≃8 Å to 100 Å on Si substrates and then jet-thin through the Si wafer to prepare the TED samples, and the other is to prepare relatively thick films (~ 1000 Å) and then do a double jet-thinning operation from each side to the interphase region (near the Si-silicide interphase). Preliminary measurements on the Pd-Si system have indicated that we get an amorphous layer for Pd films less than about 15 Å and then polycrystalline Pd_2Si (288 H) formation for films thicker than this. Figures 1 and 2 show

† This research was supported in part by the Joint Services Electronics Program under Contract F44620-76-C-0089, and by the Office of Naval Research.

typical TED patterns for 25 Å and 12 Å sputtered films of Pd on (100) Si. Both samples were unannealed. More extensive measurements may indicate that we are indeed seeing the membrane region for the thinner films.

The Pt, Ni, and Co systems also form silicides upon deposition (without annealing) as indicated by TED and/or x-ray diffraction. These systems are more complicated than the Pd case because they each form more than one silicide in the low temperature regime and so we are not as far along in our investigations for these systems. In addition, the double etching process is difficult in the Pt system because the etches tend to undercut the Pt by etching the silicides faster than Pt. In the Ni-Si system, we have observed formation of the $Ni_2Si(\delta)$ phase upon deposition using TED (not visible in x-ray) and also NiSi using x-ray diffraction. We have not as yet sorted out the morphology of these polycrystalline regions, nor have we looked for amorphous regions.

One of the things that needs to be studied in more detail is the role of interfacial oxygen on the interphase region. In this regard, Figs. 3, 4, and 5 show TED's of a 700 Å film of Co on Si annealed at 450° C for 30 minutes, which has subsequently been double jet-thinned to expose the interphase region. Figure 3 shows polycrystalline Co_2Si formation and faint rings of Co_2SiO_4. Figure 4 shows another region in the interphase where the Co_2SiO_4 rings are dominant. Different regions in the interphase are brought out in the TED due to unevenness of the etching process. Finally, in Fig. 5 we show another region in the interphase where a very amorphous structure is observed.

We plan to continue our efforts to characterize the interphase region in these systems more fully than has been done in the past, and in addition, study the effects of various parameters such as substrate orientation, substrate preparation, sputtering parameters, substrate bias and annealing, on the interphase structure and growth kinetics. In this regard we expect to shortly begin Auger and Schottky barrier measurements to supplement the structural information we are now obtaining.

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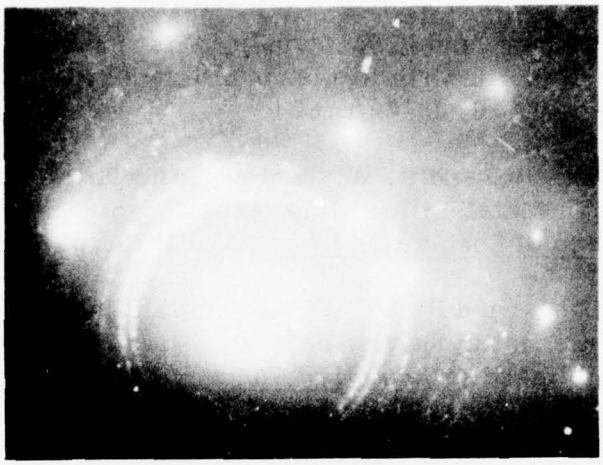

Figure 1. TED of 25Å Pd on (100) Si Showing Pd_2Si Formation.

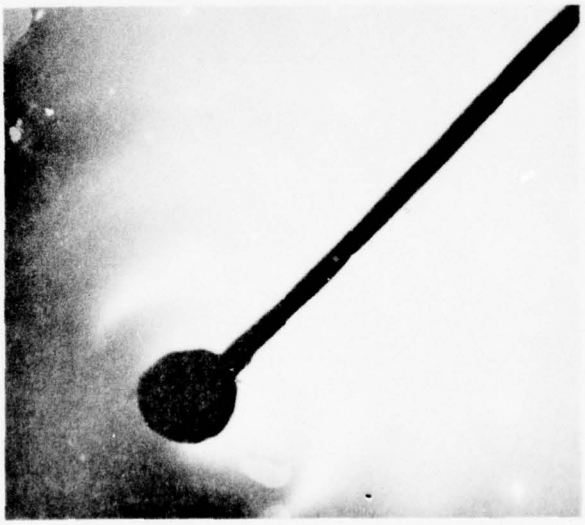

Figure 2. TED of 12 Å Pd on (100) Si Showing Amorphous Rings.

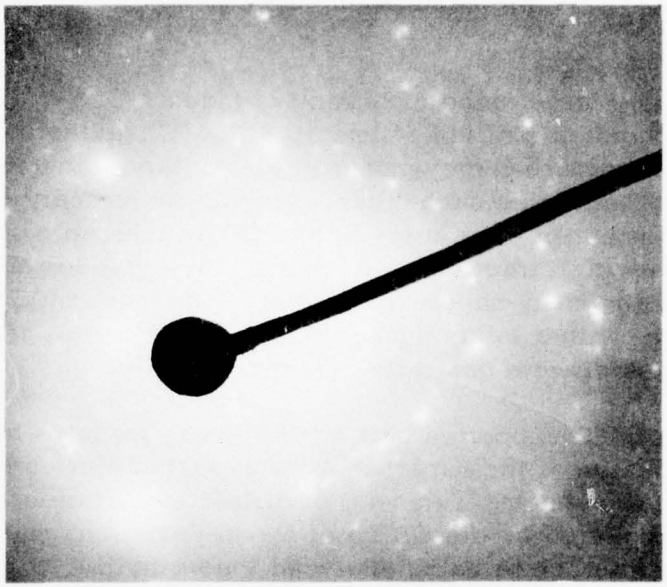

Figure 3. TED of Interphase of 700Å Co on (100) Si Showing Co_2Si Formation.

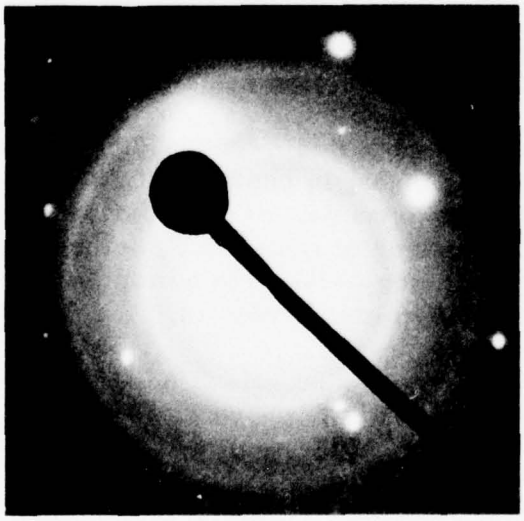

Figure 4. Same as Figure 3 Showing Co_2Si Rings.

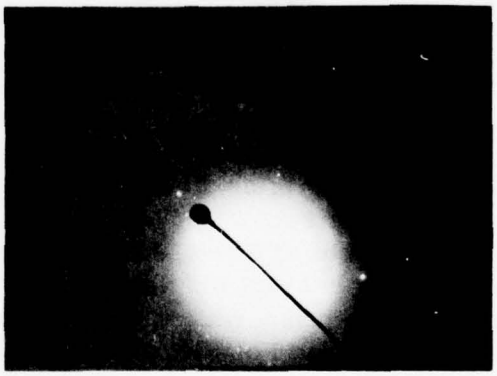

Figure 5. Same as Figure 3 Showing Highly Amorphous Ring Structure.

C. INTEGRATED OPTICAL BEAM ADDRESSER †

Professor A. B. Buckman

The very large range of refractive index (2.2→2.7 at 6238 Å) accessible by photolysis of PbI_2 films at ~ 165°C raises the possibility of multiple exposure of a large number of elementary holograms in guided wave structures containing such films. As with an ordinary thick phase hologram, the number of elementary holograms which can be multiply exposed increases with refractive index range. In a guided wave geometry a device containing many superimposed Bragg gratings could function as a beam addresser with a large number of resolvable spots, if the mode propagation constant were controlled electrooptically.

In the JSEP-supported part of this work, we have been concerned primarily with design of the experiment for exposing elementary holograms in PbI_2 films, allowing measurement of diffraction efficiency. In a related project sponsored by the Office of Naval Research, multiple layer waveguiding structures are being analyzed theoretically, with special attention given to structures where small refractive index variations in one of the media produce larger variations in mode effective index [1-3].

To record a hologram in hot PbI_2, random phase changes in the interfering beams due to air convection near the heated film must be eliminated. To accomplish this, a prism of triangular cross section was placed in optical contact with the glass substrate. A diverging beam from an argon laser, incident on the opposite edge of the triangular prism, was observed to produce good quality interference fringes, of period ~4000-5000 Å (depending on prism geometry and refractive index) in photoresist coated on the glass substrate. The glass substrate forms part of an enclosed box, which is held at a temperature of 165°C by means of resistance heating. The box is heavily insulated, to avoid producing convection currents in front of the prism which would destroy the interference pattern. The first experiments on PbI_2 films will begin shortly.

By measuring the diffracted intensity of the phase gratings we produce, we can evaluate diffraction efficiency. This will be done for both guided and unguided modes, but emphasis will be on the guided-

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wave geometry. Results for the guided-wave case will be interpreted using the theory of guided waves in multilayer waveguides, including recent contributions to the theory of periodic, stratified media [4].

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D. MECHANISM FOR LARGE REFRACTIVE INDEX CHANGE IN PHOTOLOYZED PbI_2 †

Professor A. B. Buckman

The very large (~0.5) refractive index change in PbI_2 that occurs upon photolysis at 150-180°C, observed by us over two years ago, has been the subject of a variety of experiments designed to determine the mechanism behind this striking effect. Ellipsometry allowed us to attribute the effect to dispersion arising from a broad, photolysis-induced band near 580 nm, which shifted to shorter wavelengths as photolysis proceeded [1]. However, the origin of this band could not be determined from optical data alone.

The experiments used to shed light on the mechanism behind the large, photolysis-induced refractive index change were: (1) spectral dependence of photoconductivity, and (2) x-ray diffraction on films photolyzed under various ambients and passivating overlayers. The experimental details are reported in Ref. 2.

The spectral dependence of the photoconductivity shows that the photolysis-induced band arises from electron transitions which produce free carriers. The x-ray diffractometry traces from films photolyzed in vacuum, air, O_2 and CO_2, and while covered with a transparent, passivating layer, show that the large refractive index change depends on the following conditions: first, gaseous iodine must leave the film, via the surface and/or grain boundaries; second, oxygen or CO_2 must enter from the atmosphere and bond with the Pb left behind, inhibiting agglomeration of neutral Pb. The defects thus formed must give rise to the observed absorption band. These results are described in detail in Ref. 2.

We intend to investigate the spatial resolution of this effect by forming phase holograms in the PbI_2 films. Since the above experiments clearly demonstrate the photochemical origin of the large refractive index change, and since amplitude hologram recording in PbI_2 has already been demonstrated [3], we expect the resolution to be sufficient for phase holography.

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† This research was supported entirely by the Joint Services Electronics Program under Contract F44620-76-C-0089.

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II. INFORMATION SYSTEMS

(II. INFORMATION SYSTEMS)

A. DESIGN OF TWO-DIMENSIONAL RECURSIVE FILTERS BY INTERPOLATION †

Professor J. K. Aggarwal and H. Chang

1. INTRODUCTION

Recursive digital filtering of two- and multi-dimensional signals is an important technique in the processing of two- and multi-dimensional data. However, the design of two- and multi-dimensional recursive filters is difficult due to the fact that polynomials in two or more variables may not, in general, be factored into lower order polynomials. Specifically, the stability test procedure for a two-dimensional filter is lengthy and tedious. Further, if the filter turns out to be unstable, there is no guaranteed procedure which may stabilize the unstable filter. These difficulties can be partly circumvented by designing two- and multi-dimensional systems as one dimensional systems. To do this, we have developed a technique for rotating the frequency response of a separable filter. In the present technique, transfer functions having rational powers of z are introduced and realized by input/output signal array interpolations.

2. MAIN RESULTS

The frequency transformation technique is one of the traditional approaches in deriving desired frequency selective filters from simple prototype filters. Extending the notion of frequency transformation to include rational powers of z_1 and z_2, one can rotate the frequency response with band contraction. To begin with, consider the transformation

$$z_1 = \hat{z}_1 \hat{z}_2^{\frac{\beta}{\alpha}}$$

where α and β are integers. The transformation has the following properties:

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(1) It may be thought of as a mapping from the unit circles of the $(\hat{z}_1, \hat{z}_2)$-domain into the unit circles of the (z_1, z_2)-domain.

(2) When $\beta/\alpha \geq 0$, the transformation is causal, otherwise it is noncausal.

(3) In the spatial domain it is equivalent to the rotation of recursion direction with a new sample interval.

(4) In the frequency domain the effect of the transformation is a rotation of the frequency response with a contraction of the bandwidth.

(5) It is clear that the stability of the resulting filter is not affected since the transformation can be viewed as a transformation of the delay unit which may be specified by both recursion direction and sampling interval.

Since we allow noninteger delays, the signal values for the transformed filter are not defined at the new grid points, so the transformation is not readily applicable to standard rectangular arrays. If one uses a suitable interpolation function that can reconstruct a continuous signal from a discrete signal, it is possible to generate an interpolated array where signal values are defined on the new grid points. In general, there are many functions available for the interpolation. Specifically, the band-limited interpolation is employed in our design. The band-limited interpolation function usually stretches from $-\infty$ to $+\infty$. To obtain an interpolation function with finite terms, we apply windowing to it. With all of these features, it is called the interpolated filter system which consists of input interpolator, (z_1, z_2)-domain rotated filter, and output interpolator. The overall frequency characteristic of the interpolated filter system is determined by the frequency characteristics of input/output interpolators and (z_1, z_2)-domain rotated filters. Several useful filters were actually designed such as a circularly symmetric low-pass filter, nonseparable band-pass filter, and a ring-shaped band-pass filter to prove the validity of our design technique. In the design of these filters, we assumed that the input signals are given as finite area arrays so that noncausal filters can be realized through the array reorientations. Also, we employed the zero-phase response since the linear phase is very important in the image processing. Actual filter characteristics turned out to be very smooth and to have excellent circular symmetry. A primary advantage of employing

separable filters in the interpolated filter system is that one may perform two- or multi-dimensional manipulations by means of a series of one-dimensional manipulations. With this scheme the same interpolated filter system may be used iteratively, together with proper array reorientations, resulting in an appreciable saving in hardware.

Since the theory and design techniques for two-dimensional digital filters are largely incomplete, in the next period we will investigate these problems further until we have fairly general theory and design techniques for those filters. Then, we hope to generalize the theory and design techniques available for one- and two-dimensional digital filters to cover the time-varying digital filters.

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B. NONPARAMETRIC DISCRIMINATION AND ESTIMATION †

Professor C. S. Penrod, Professor T. J. Wagner,
and L. P. Devroye

In the nonparametric discrimination problem, a statistician observes a random vector X taking values in $\mathbb{R}^m$, and wishes to estimate the value of an associated random variable θ which takes values in $\{1,\ldots,M\}$. The random variable θ is usually referred to as the state of the observation X. The statistician assumes no knowledge of the probability distribution of (X,θ) other than what may be inferred from his data, a sequence $(X_1,\theta_1),\ldots,(X_n,\theta_n)$ of independent identically distributed random vectors with the same distribution as (X,θ), given by

$$\text{(a)}\quad P\{\theta = j\} = \pi_j \text{, and} \qquad (1)$$

(b) given that $\theta = j$, X has probability measure μ_j on the Borel sets of $\mathbb{R}^m$.

It is also assumed that (X,θ) is independent of the data.

A discrimination rule is simply a specific method of choosing an estimate of θ from the data and the observed value of X. If we allow $\hat{\theta}$ to denote the rule's estimate of θ, we can define the conditional probability of error for the rule with a given data set by

$$L_n = P\{\hat{\theta} \neq \theta \mid (X_1,\theta_1),\ldots,(X_n,\theta_n)\}\ . \qquad (2)$$

The strong law of large numbers assures that the relative frequency of errors will converge to L_n if we use the rule and the given data to estimate the values of θ for a large number of independent observations. Hence, L_n is a measure of the performance of the rule with a given data set.

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The nonparametric estimation problem is quite similar to the discrimination problem in its formulation. The principle difference is that θ (which is now called the parameter associated with X) is allowed to take values in $\mathbb{R}^p$ rather than $\{1,\ldots,M\}$, and we now assume that (X,θ) is a random vector with joint distribution $F(x,\theta)$. We also assume that a loss function L is given, defined on $\mathbb{R}^p \times \mathbb{R}^p$ so that $L(\theta,\hat{\theta})$ is the loss incurred when $\hat{\theta}$ is the rule's estimate of θ. We now define the conditional expected loss of a rule with a given data set as

$$L_n = E\{L(\theta,\hat{\theta}) \mid (X_1,\theta_1),\ldots,(X_n,\theta_n)\} . \tag{3}$$

As in the discrimination problem, L_n measures the performance of the rule with a given data set since it is the average loss which will be incurred if the values of θ are estimated for a large number of independent observations.

In both the discrimination and estimation problems, if the underlying distribution of (X,θ) is known, it is usually possible to construct an optimal estimate $\theta^*(X)$ of θ (e.g., in the estimation problem one may have to be satisfied with an ϵ-optimal estimate). Such an estimate does not depend on the data and is optimal in the sense that its probability of error or expected loss is less than or equal to that of any other rule. The optimal rules are known as Bayes rules, and their expected loss (or probability of error) is denoted R^*. R^* then provides a standard of excellence against which we can compare the performance of all nonparametric rules.

One of the basic approaches to the nonparametric discrimination problem is suggested by the manner in which an optimal Bayes rule is constructed. Let

$$p_j(X) = P\{\theta = j \mid X\} \quad , \quad 1 \le j \le M.$$

Then it is easily shown that a Bayes optimal rule results if, given X, we choose $\theta^*(X) = j$ if

$$p_j(X) \ge p_i(X) \quad \text{for all} \quad i \ne j.$$

(Ties can be broken by employing some appropriate form of randomization.) Of course, in our nonparametric case, the functions $p_j(x)$ are unknown since they depend on the distribution (1). For example, if the measures μ_j are absolutely continuous with respect to Lebesgue measure, then there are probability density functions f_j, $1 \le j \le M$ corresponding to the μ_j. These densities can be used to define versions of $p_j(x)$ by

$$p_j(x) = \begin{cases} \pi_j f_j(x)/f(x) & , \text{ if } f(x) > 0 \\ 0 & , \text{ if } f(x) = 0, \end{cases} \tag{4}$$

where $f(x) = \sum_1^M \pi_i f_i(x)$. This suggests that the nonparametric problem could be approached by using the data to estimate the density functions, and then using the density estimates in place of the true densities in the manner described in (4). Such rules are known as "two step" rules. In Devroye and Wagner [1] the results of an extensive study of density estimation and two step rules are presented. Conditions are shown for which consistent density estimates yield rules for which $L_n \to R^*$ in probability or with probability one. In addition, a detailed study is made of the Parzen-Rosenblatt [2, 3] and Loftsgaarden-Quesenberry [4] density estimates, extending many of the previously known results.

Another approach to the nonparametric discrimination problem is the familiar nearest neighbor rule. This rule simply chooses $\hat{\theta} = \theta_i$ if X_i is the closest observation to X from the data. Various generalizations include the k nearest neighbor rule where $\hat{\theta}$ is chosen to be the state which occurs most frequently among the k nearest neighbors to X. Among the well-known properties of nearest neighbor rules is the fact that if k is allowed to depend on n in such a way that $k \to \infty$ and $k/n \to 0$, then it is possible to have $L_n \to R^*$ (Fix and Hodges [5]). In (1) this result is extended to a more general class of nearest neighbor rules which weight the influence of the closer observations more heavily.

Nearest neighbor rules have also been used as solutions to the nonparametric estimation problem (Cover [6]). The k nearest neighbor rule's estimate of θ is obtained by averaging the parameters associated with the k closest observations to X from the data. Cover shows conditions for which

$$EL_n \to (1 + 1/k)R^*$$

for k nearest neighbor rules with squared-error loss functions. In Penrod and Wagner [7], these results are extended to show that

$$L_n \to (1 + 1/k)R^* \text{ in probability.}$$

The significance of this result is that it concerns the convergence of L_n for a single long data sequence as opposed to the convergence of the average value of L_n averaged over a large number of long data sequences. In addition, conditions are given for which $L_n \to R^*$ in probability for k nearest neighbor rules which have $k \to \infty$ and $k/n \to 0$.

The results mentioned thus far have all been asymptotic results concerning the performance of various rules with large data sets. For obvious reasons, however, the designer of a nonparametric discrimination or estimation rule is always interested in knowing the value of L_n for this rule with the data available to him. But, due to the fact that it cannot be computed without knowledge of the underlying probability distribution of (X,θ), which is not available, he must be content with an *estimate of the true value of* L_n. In (1) the properties of three different estimates of L_n for discrimination rules are studied. These estimates are known in the literature (see Toussaint [8]) as the deleted estimate, the holdout estimate, and the resubstitution estimate. For linear discrimination rules, local rules, and two step rules, conditions are shown for which $P\{|L_n - \hat{L}_n| \geq \epsilon\}$, where $\hat{L}_n$ is one of the above estimates of L_n, can be bounded independently of the distribution of (X,θ). These results allow the designer of a rule to construct confidence intervals for the performance of his rule. These results are extended to nonparametric estimation rules in [7]. The report [7] also contains the results of an extensive simulation study of the performance of deleted and holdout estimates of L_n with nearest neighbor discrimination and estimation rules.

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C. A COMPUTER ARCHITECTURE FOR BYTE STRING AND VECTOR OPERATIONS †

Professor T. A. Welch and H. L. Tredennick

1. INTRODUCTION

This report presents the findings of a computer design experiment carried out at The University of Texas at Austin. A computer architecture for variable word length processing is proposed to support high-level languages. The proposed architecture uses byte iterative processing and specialized hardware. The specialized hardware, shown in Fig. 1, consists of a byte serial ALU and a separate address generator and memory buffer for each operand byte stream.

Variable word length processing has been investigated to determine which subtasks are difficult and which are easy and to determine the feasibility of variable word lenth processing. Additionally, requirements and implementation strategies for the ALU, operand address generation, and memory buffering have been analyzed.

Use is made of cheaper and more complex logic and memory componenets to effect a more complex design for simpler programming. The processor is designed to manipulate more complex operands rather than provide more complex operations. The processor is designed for processing operands which might be unequal length elements, arrays, or arbitrary data structures. Design centers on processing for character strings and variable-length arithmetic, but scientific processing is not ignored.

2. VARIABLE FIELD LENGTH PROCESSING

The following problems are associated with variable field length processing:

(1) It is impractical to store either complete variable-length operands or partial results in registers.

†This research was supported in part by the Joint Services Electronics Program under Contract F44620-76-C-0089, and NSF Grant GJ-42514.

(2) Variable-length remove and replace are difficult in a fixed word length memory with random operand placement.

(3) Operand alignment may be required for unequal length operands.

(4) Simultaneous operand fetching is desirable in an iterative solution which uses multiple operand streams.

(5) Sign and exponent placement are significant problems due to the serial scan nature of processing.

(6) Optional scan direction is desirable.

(7) Sign, zero, or blank extension is desirable for processing unequal length operands.

3. VARIABLE LENGTH ARITHMETIC

Iterative processing is preferred over length limitation because limiting operand lengths to the maximum register or accumulator length was felt to be too restrictive. Byte serial processing was selected over bit and nibble processing because the narrower data paths for bit and nibble transfers slow processing. Data lengths greater than a byte reintroduce many problems (such as shifting, masking, and alignment) and ALU costs increase rapidly with width.

The two viable choices for number representation and scan direction are: (1) a right-to-left scan with a two's complement number representation or, (2) a left-to-right scan with a sign and magnitude number representation. The two's complement representation and right-to-left scan were chosen because of greater ease and efficiency of the addition scan.

Character and integer instruction implementations are simple and multiply and divide instruction implementations are difficult. The character instructions, such as move, compare, shift, and Boolean, and the integer instructions, such as add, subtract, move, compare, and replace all require only a simple single pass scan. The multiply and divide instructions require multiple scans and complex scanning sequences.

4. ALU IMPLEMENTATION

Implementation of a byte serial ALU capable of supporting the basic character and integer operations would require about 52 IC's. The incremental increase in ALU hardware required to support floating-point operations is about 50%. An increase of about 50% over hardware for the basic ALU will support multiply operations. Additional hardware to support the divide instruction is about an 80% increase over hardware to support the multiply. A complete implementation requires about 160 IC's.

Time to perform a 32-bit byte serial add is about 480 μsec compared to about 160 μsec for a 32-bit parallel add. Performance of the add in a byte serial manner represents about a 20% degradation in the total instruction execution time. Execution of a 32-bit multiply in byte serial fashion requires about a sixteenth of the hardware for a parallel multiply and is about sixteen times slower. A byte serial multiplier is about equal in speed and cost to a bit serial implementation. A byte serial divide implementation is about the same cost as a fixed length divide, but is about half as fast.

5. OPERAND ADDRESSING

All of the problems associated with variable-length processing affect the design of the operand address generators. A three address instruction format of the form A op B → C was selected for the processor design and a separate address generator was provided for each operand stream.

The operand address generator provides the following element addressing features:

(1) Optional element scan direction

(2) Terminate on short element (Truncation)

(3) Repeat short element

(4) Extension of leading/trailing byte/zeroes

(5) Element alignment

The operand address generator provides the following vector addressing features:

(1) Skip internal fields

(2) Vector chaining

(3) Repeat vector

(4) Repeat last element

(5) Terminate on short vector

(6) Optional vector scan direction

The Operand Address Generators can provide byte addressing for variable word length operands, addressing for simultaneous byte streams, operand alignment, and operand extension. In addition, the address generators can provide complex addressing sequences required to implement complicated iterative processes, and support array operands with interspersed data or concatenated fields. Implementation of the address generators to support these operands and operations requires complex control, many data paths, and much interprocess communication. Each Operand Address Generator requires about 90 IC's for implementation (using a mix of standard and Schottky TTL).

6. VARIABLE FIELD LENGTH BUFFERING

Problems confronted in design of the memory buffer include the lack of variable-length registers, accessing of variable-length operands, operand alignment, and provision of simultaneous data streams.

The following observations can be made about the requirements for implementing the buffer: (1) It must be fast enough to compensate for the lack of variable-length registers; (2) it must be large enough to hold several operands of typical size; (3) automatic buffer allocation is required because allocation is too difficult and dynamic for the programmer to manage; (4) dynamic byte sequence control is desirable for efficiency; (5) the ALU requires a byte interface and the memory, a word or block interface; (6) there should be a short initiation latency (time from termi-

nation of one process to the beginning of the next should be short); and (7) multiple access paths are necessary for efficient processing using simultaneous data streams in an iterative process.

Four schemes were considered for implementation: a single word buffer, a single cache buffer, a separate queued buffer for each operand stream, and a separate cache buffer for each operand stream.

Single Word Buffer. The single word buffer has the advantages of simplicity, limited data currency problems, and short start-up time. It has the disadvantages of being slow, not allowing block transfers, and holding only a single word of previous results (for retrieval).

Single Cache. The single cache buffer has the advantages of allowing main memory block transfers, providing some register-like capabilities, being faster than the one word buffer, and saving main memory cycles. The single cache suffers from access priority selection problems and requires sequential access. Conventional cache design improvements are of minimal avail because they are designed to reduce access conflicts for space. In an iterative processor employing simultaneous data streams, access conflicts in time are much more important than conflicts for space due to the parallel nature of the data streams.

Queued Buffer. Separate queues for each operand stream provide simultaneous operand streams, simplify buffer allocation, and can be fast enough to support a byte serial ALU. The queued buffering scheme has many disadvantages: there may be multiple copies of data, queue searches are difficult, queue control is complex, the queues require much data and address storage, queues are inflexible, and initialization and emptying are slow processes.

Separate Cache Buffers. The separate cache buffering scheme, shown in Fig. 2, provides the following advantages: virtual variable-length registers, hardware controlled allocation, byte addressing for the ALU byte streams and block addressing for main memory, and simultaneous data paths for the separate data streams. It has the disadvantages that there may be multiple copies of the data, many address paths and comparisons are required, complex control functions are required, and perverse address sequences exist which defeat the allocation scheme (direct mapping).

7. CONCLUSIONS

The proposed architecture has been evaluated and shows that byte serial iterative processing of variable-length operands is feasible. Variable word length operations are significantly faster on the proposed machine than on any fixed word length machine in its class(minicomputers). Fixed word length operations are faster than their software counterparts on a fixed length machine, about as fast as a microprogrammed implementation, and slower than specialized hardware.

The MSI and LSI technologies allow sophisticated ALU design. The byte serial ALU is not the processing bottleneck.

Operand byte access is the limiting factor. Stores are slower than reads and multiple stores may be required.

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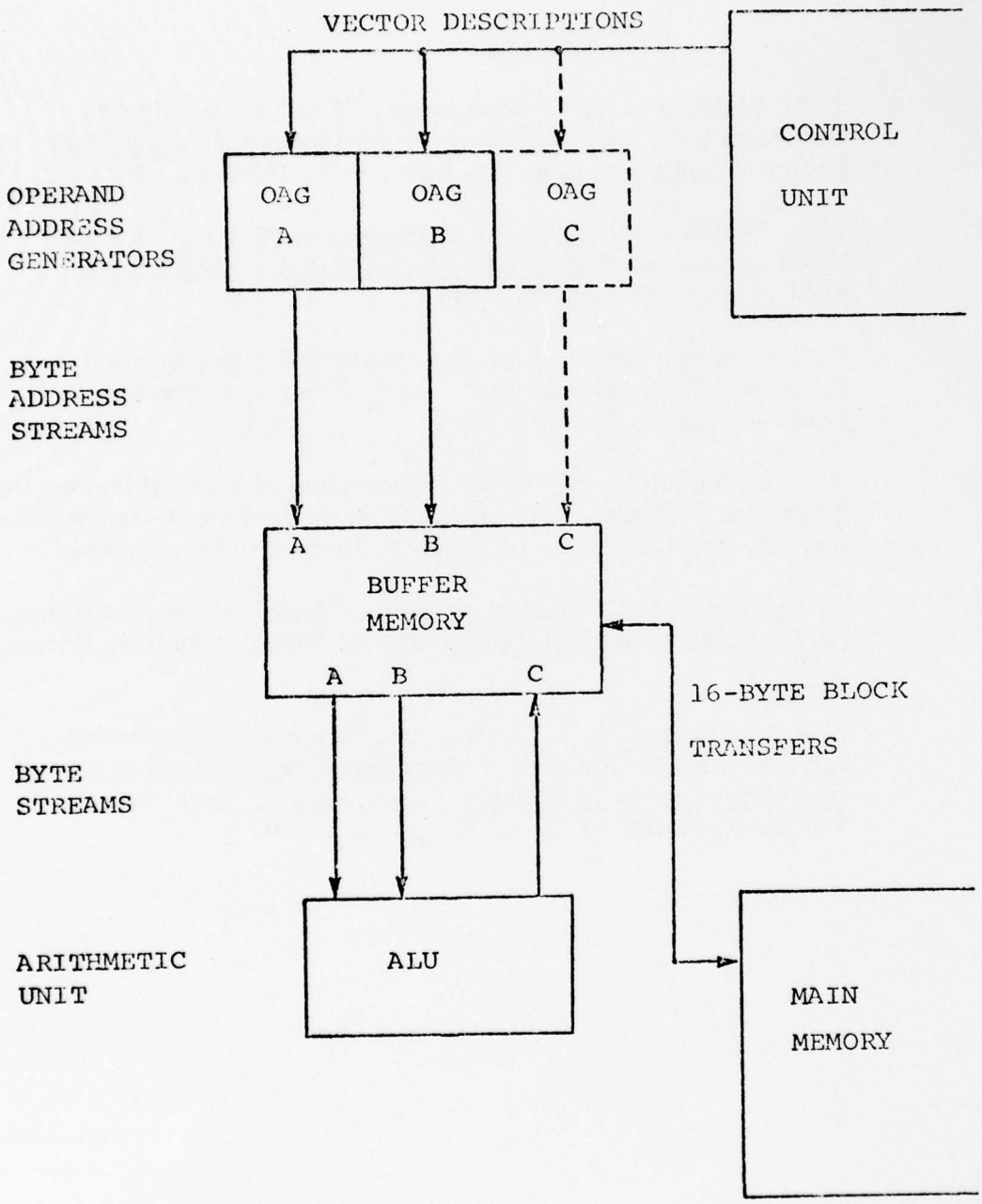

Figure 1. Variable Length Data Processors.

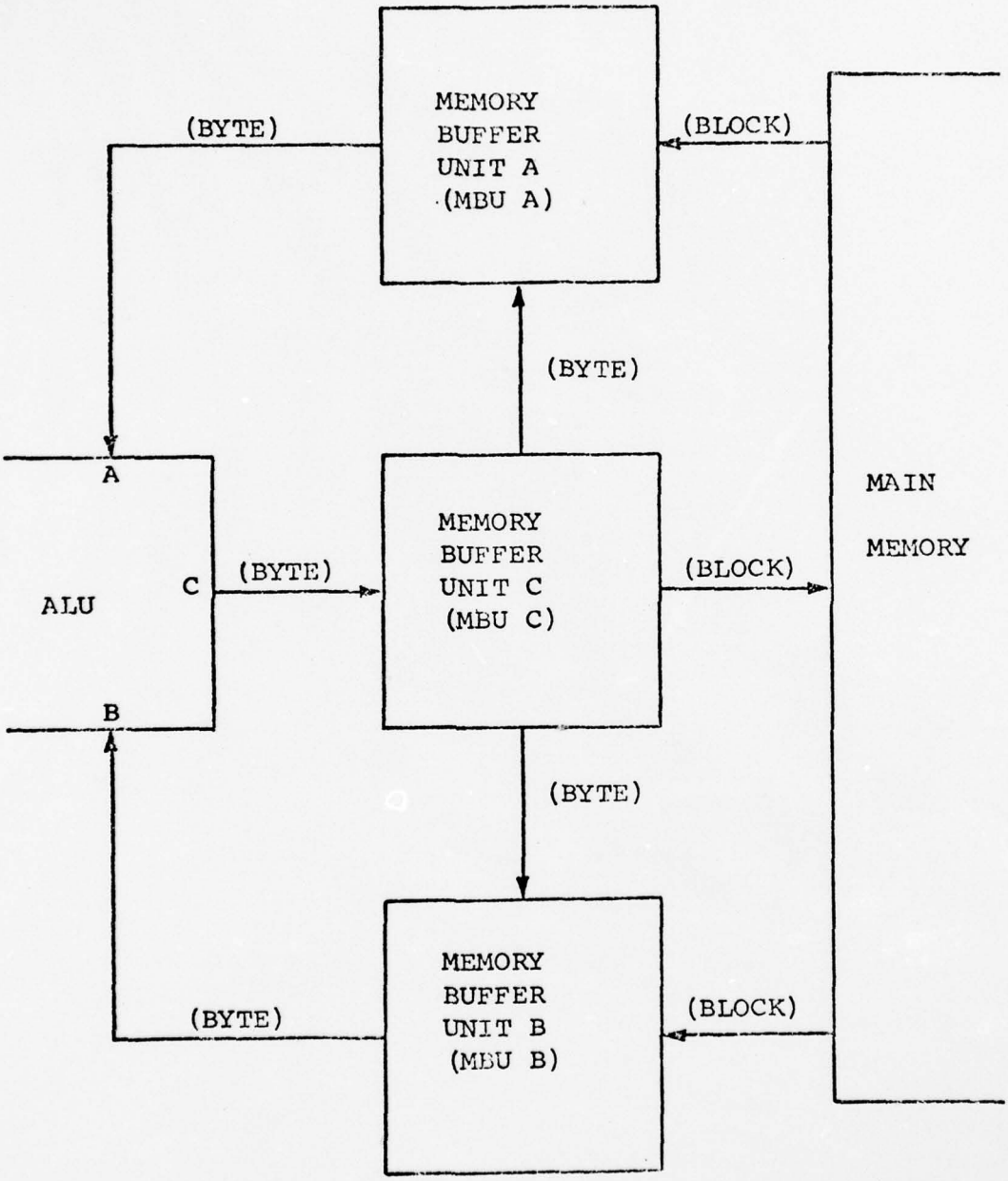

Figure 2. Separate Cache Memory Scheme.

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III. ELECTRONIC COMPUTERS

(III. ELECTRONIC COMPUTERS)

A. SIMULATION AND RELIABILITY OF FUNCTIONAL DEVICES†

Professor S. A. Szygenda, Professor E. W. Thompson, and A. K. Bose

Simulation of logic nets has been used extensively for the verification of logic design and to study the reliability of logic systems. The level of simulation however, has been restricted to simple Boolean gates and flip-flops. This restriction has not posed any severe problems to users in the past, since the size of nets being used has been small and the devices simple. With the current trend towards design of large systems with the use of complex devices, logic simulation has become inadequate. Simulation at a functional level provides a possible solution to this problem.

This report discusses several aspects of this trend. Major problems that remain unsolved in the area of functional level simulation are discussed and solutions offered for some of them. Two major functional devices are examined and ways to improve their reliability are suggested.

The lack of understanding that exists for functional devices indicates that functional level simulation has to evolve from gate level simulation. Moreover, since the functional description of a system is not adequate to perform an in-depth analysis, such as prediction of hazards and races, an interchangeable functional and gate level description of systems is suggested [1]. Such a capability would provide for efficient macroscopic simulation by using the functional description, or accurate timing and failure analysis by using the gate level description.

Under certain situations, it may be possible to simulate a functional device as accurately as a gate. This can be realized by using a data structure of the type shown in Table 1 to represent multivalued signals at the input of a system [2].

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Table 1. Signal Representation.

Symbol	Signal Description	Current Value	Future Value
1	Logical 1	1	1
0	Logical 0	0	0
U	Upward Transition	0	1
D	Downward Transition	1	0
E	Unknown Signal	0 1	0 1

Using this data structure and the known values of the input signals, the following binary vectors may be defined:

(1) The current input vector:

$$\vec{x}_c = \langle x_{1c}, x_{2c}, \ldots x_{nc} \rangle$$

where x_{ic} is the current value of the input signal x_i.

(2) The future input vector:

$$\vec{x}_F = \langle x_{1F}, x_{2F}, \ldots x_{nF} \rangle$$

where x_{iF} is the future value of the input signal x_i.

(3) Intermediate input vectors:

$$\vec{x}_{Ij} = \left\{ \langle x_{1k}, x_{2k}, \ldots x_{nk} \rangle \mid x_{ik} \in \{x_{ic}, x_{iF}\} \right\}$$

where the vectors are generated by taking all possible different combinations of current values and future values of the inputs.

These binary vectors can be used to evaluate a binary description of the functional device, and the outputs obtained from the current and future input vectors (y_c and y_f) can be combined using Table 1 to yield a multivalued output. The outputs obtained from the intermediate inputs (y_I) can be used to predict hazards by executing the following steps:

Step 1: Using the intermediate input vectors, generate intermediate outputs. $y_{Ii} = f(\vec{x}_{Ii})$

Step 2: If $Y_c = y_F$ and $y_{Ii} \neq y_c = y_F$, then a static hazard exists.

Step 3: If $y_c \neq y_F$, then if all y_{Ii} are identical, no dynamic hazard exists. If $y_{Ij} \neq y_{Ik}$ for any j and k, then a dynamic hazard is present.

The analysis of faulty behavior of functional devices, especially those of a sequential nature, poses severe problems. A single fault in a serial shift register, a functional device that has wide applications in computer systems, has a global corrupting influence on the data propagating through it. The correction of errors introduced in the data is impossible, but the detection of errors can be realized through a nominal amount of redundancy [3].

An analysis of various shift register configurations shows that the effect of a single fault is always restricted to a single type of data bit (0 or 1). This result indicates that errors in a shift register can be detected by counting the number of ones entering the shift register and comparing this with the number of ones coming out of it. A hardware scheme to do this can be realized by using an up/down counter. Since a counter requires around $\log_2 N$ flip-flops to count up to N, while a N bit shift register requires N flip-flops, the redundancy involved is of the order of $\log_2 N$.

A computer input/output controller is a functional unit whose complexity is very high (300-400 gates). Since these controllers are used to interface with electromechanical input/output devices, their failure could be catastrophic. To prevent such a situation, these units are often duplicated. A detailed analysis of its organization reveals

that it can be made highly reliable by introducing only 30% additional hardware [4].

These results indicate that great cost savings can result from a close analysis of functional devices. The often-used approach of duplicating systems is uneconomic and unnecessary. The only feasible way to do the analysis is by simulating the system. As simulation is an expensive process and is required at various levels of the design phase, the capability to simulate at a functional level is essential.

Since functional level simulation is a fairly new concept, the current state of the art is far from satisfactory. There are problems associated with the description of functional devices, simulation procedures, simulation accuracy and fault handling strategies that need to be solved before functional level simulation is meaningfully realized.

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B. DEVELOPMENT OF METHODOLOGIES AND MODELS FOR THE DESIGN OF DIGITAL SIMULATION SYSTEMS WITH VERY HIGH PERFORMANCE†

Professor S. A. Szygenda and Yu-Huei Jea

1. INTRODUCTION

Digital simulation is a mandatory tool in most of today's design automation systems. An ideal simulator should satisfy three major criteria, namely, accuracy, cost-effectiveness, and ease of use [1]. This report outlines the methodologies and models developed to fit these requirements. Detailed descriptions can be found in [2].

2. BOOLEAN VECTOR E-ALGEBRAS

Due to the advances of technology, there is an increasing interest in multivalued logic systems where more than two logical values are used. For example, the following topics which are important in the computer area, are related to multivalued logic: multivalued logic circuits, digital simulation, test generation, multibus digital circuits, etc.

In the application of multivalued logic, each logic value could be represented by a Boolean vector, i.e., a vector with binary components (0 or 1). Therefore it is quite important to have a thorough understanding of properties embedded in the algebraic structures, using Boolean vectors as basic operands. Here we briefly introduce a new mode of complement and a new type of algebra.

A P mode complement is a permutation which is not an identity mapping. Only when a permutation is equal to the product of disjoint transpositions can a P mode complement have the order of 2.

An E-algebra $\{s,1,+,'\}$ is a set S with two binary operations $\cdot$ and $+$ and one unary operation $'$ such that for all $x,y,z \in S$ we have

E1.	$x \cdot x = x$	$x+x=x$	(Idempotent)
E2.	$x \cdot y = y \cdot x$	$x+y=y+x$	(Commutative)

†This research was supported in part by the Joint Services Electronics Program under Contract F44620-76-C-0089, and in part by the Naval Surface Weapons Laboratory N 60921-76-C-A168.

E3. $x\cdot(y\cdot z)=(x\cdot y)\cdot z$ $\quad x+(y+z)=(x+y)+z$ (Associative)

E4. There exists $0,1 \in S$ such that

$x\cdot 0=0$ $\quad x+0=x$

$x\cdot 1=x$ $\quad x+1=1$ (Universal Bounds)

E5. For every $x \in S$, there exists a unique $x' \in S$ such that

$x''=x$ (Involution)

E6. $(x\cdot y)'=x'+y'$

$(x+y)'=x'\cdot y'$ (de Morgan)

A Boolean vector E-algebra is an E-algebra $\{S,.,+,'\}$ where S is a Boolean vector set, . and + are two Boolean vector binary operations, and ' is a Boolean vector unary operation.

One application of Boolean vector E-algebras has been suggested in the digital simulation area. It provides one way to define the information representation for signal models in a parallel simulation environment.

3. VARIOUS APPROACHES TO REPRESENTING SIGNAL MODELS AND RELATED LOGICAL OPERATIONS

In the design of a digital simulator, one of the first decisions to be made is to determine how many signal states we want to propagate. Then we must decide the information representation of these signal values. Also the implementation of related logical operations has to be settled. Usually the good representation of operations depends on the proper representation of operands, and vice versa.

Four major approaches can be used in various situations:

(1) Table look-up method

(2) Switching theory approach

(3) Relational approach

(4) Boolean vector E-algebra approach

Although global optimization of information representation might be quite difficult or even impossible, near optimal representations can be achieved through the optimal implementation of those types of elements which occur most frequently, in most digital networks.

4. GATE MODELING AND TIMING ANALYSIS ALGORITHM

Gates are the basic elements of digital circuits. They may have several inputs but only one output. Two operations are normally performed by them:

(1) V-operation (or value operation)

(2) D-operation (or delay operation)

The V-operation of any gate is usually deterministic in nature and clearly defined by the corresponding operation table. The complexity of the D-operation, however, depends on the delay model adopted. It can be as simple as an identity mapping in a zero delay model, or as complicated as a composition of the following four mappings in a precise delay model: P-mapping , S-mapping, A-mapping, and T-algorithm.

T-algorithm (timing analysis algorithm) is not simple in the three-valued model [3,4] and even more complicated in the five-valued model. In this research, we not only find a five-valued T-algorithm, but also prove its accuracy and functional completeness.

There are four types of delay parameters used in the precise delay model: d_{mR} (min. rise delay), d_{MR} (max. rise delay), d_{mF} (min. fall delay), and d_{MF} (max. fall delay). Their usage in our model, which is different from [5], can be summarized as follows:

- Add d_{mR} when the input signal changes to U.
- Add d_{MR} when the input signal changes to 1.
- Add d_{mF} when the input signal changes to D.
- Add d_{MF} when the input signal changes to 0.
- Add min (d_{mR} , d_{mF}) when the input signal changes to E.

5. HIGH-LEVEL INPUT LANGUAGES FOR DIGITAL NETWORKS

A system which is difficult to use usually finds little use. This statement gives rise to the important question of how to represent the digital network such that the user can easily transcribe it into a ready-for-input format.

Postfix notation, also known as Polish notation, is a very convenient method of incorporating both the simplicity of a functional description and the preciseness of a structured description. For example,

A B C 3+ D E F 4

denotes a circuit with an OR gate of three inputs: A, B, and C, and an AND gate of four inputs: one is the output of the above OR gate, and the others are D, E, and F.

Some modifications can be made so that we can represent non-tree type circuits, such as circuits with feedback, reconvergent fanout, etc. Also functional elements can be easily represented in the modified postfix notation.

In order to accomplish further improvements over the coding efficiency, some element type hiding techniques can be used. Thus we include a declaration paragraph before the postfix expression. For instance, the above example can be rewritten to be

BEGINDECLARE 3+ : G1; 4. : G2;ENDDECLARE

A B C +G1 D E F #G2

6. CONCLUSION

The models and methodologies given above present a practical approach to the design of a digital simulation system which is cost-effective, accurate, and easy-to-use. The effort is directed at both gate-level and functional simulation. The implementation problem has also been considered. These have definitely pushed the state of the art in the technology of digital simulation.

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C. COMPUTER SOFTWARE SYSTEM RESEARCH IN THE AREA OF MODULE INTERFACE †

Professor Ed Thompson and Ali Mohseni

The overall objective of this research is to reduce the high costs of software systems, which is the major cost of practically any computer application today. In order to achieve this, two approaches have been selected.

The first approach in this research is the development of procedures and languages for the formal specification and verification of the data interfaces between program modules. The research on data interfaces between program modules is based upon the development of a data interface specification language and its implementation.

The second approach is focussed on modular programming in COBOL. The type of the module and the way of passing parameters has some effect on costs associated with execution time and storage spaces. For a particular problem, good questions to be answered are: "What type of module?" and "How are parameters passed?"

A preliminary module interface specification language, MIS-1, has been designed, and a precompliler named BRIDGES, which supports the application of MIS-1, has been implemented and debugged. A MIS-1/ BRIDGES users manual has been written, and experience in using MIS-1 and BRIDGES has been gained in a variety of contexts. An evaluation of that experience has been completed. Four general observations can be made:

(1) MIS-1 allows powerful validation algorithms to be executed by BRIDGES, but makes more difficult the application of the technique of data hiding.

(2) The reaction of programmers to using MIS-1 is to partition a program into fewer modules and to use single modules to implement data abstractions.

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† This research was supported entirely by the Joint Services Electronics Program under Contract F44620-76-C-0089.

(3) BRIDGES spends most of its time doing I/O and scanning Fortran statements rather than performing its validation routines.

(4) The validation algorithm in BRIDGES is heuristic rather than rigorous.

Based on observations 1 and 2 above, a new specification language, MIS-2, has been designed to be more concise and to incorporate data hiding. Observation 3 implies BRIDGES could be integrated into a compiler with minimum overhead, and optimization algorithms could be used, i.e., incorporate compliler flow analysis algorithms as part of its validation technique.

In the area of modular programming in COBOL, a series of small programs were designed in COBOL to answer the following questions:

(1) Effect of type on parameter costs

(2) Parameter costs vs. the number of parameters

(3) Implementation costs of a module

(4) Data reference costs

(5) Method of parameter passing

(6) Segmentation and its limits

The results from their compilation and execution on four different computers, the Xerox SIGMA-5, the CDC-6600, the DEC PDP-10, and the IBM 360 are being analyzed.

From these experiments, we will obtain some information which will give us a better understanding of the trade-offs involved in using sections, as opposed to subprograms, so that intelligent choices can be made for system implementation. Also, this information will be useful in making recommendations for the implementation of future COBOL compilers.

(3) BRIDGES spends most of its time doing I/O and scanning Fortran statements rather than performing its validation routines.

(4) The validation algorithm in BRIDGES is heuristic rather than rigorous.

Based on observations 1 and 2 above, a new specification language, MIS-2, has been designed to be more concise and to incorporate data hiding. Observation 3 implies BRIDGES could be integrated into a compiler with minimum overhead, and optimization algorithms could be used, i.e., incorporate compliler flow analysis algorithms as part of its validation technique.

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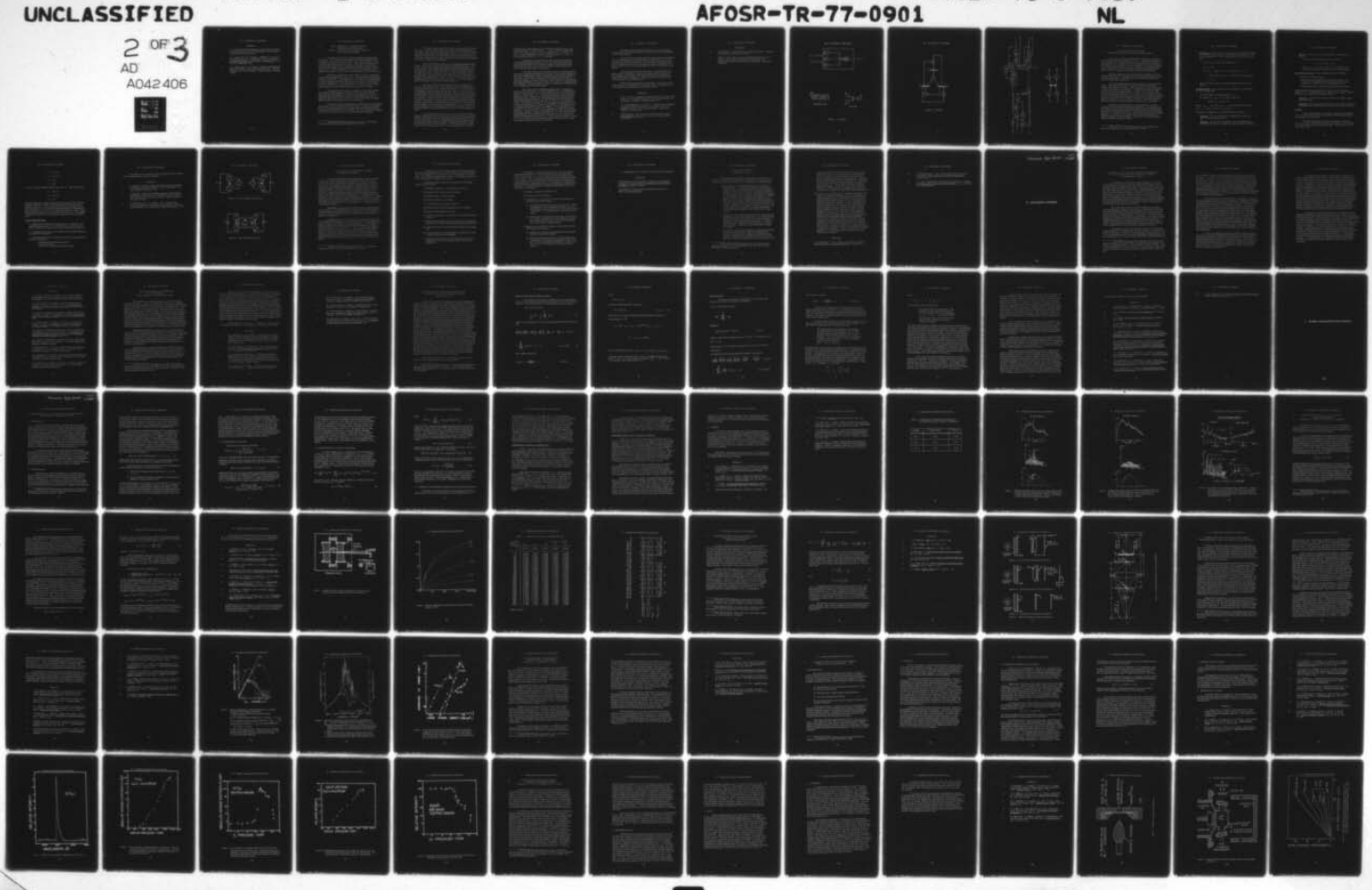

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D. FAULT TOLERANCE OF CONTROL CIRCUITS DESIGNED USING PETRI NETS †

Professor Tilak Agerwala, Professor Ed Thompson,
and Ernesto Pacas-Skewes

Petri Nets [5] are a useful tool for the design and description of systems. They can be used to represent concurrent operation and arbitrariness, and can describe systems at various levels of detail. They are especially suited for control circuits. Their use in the design of circuits that perform algorithmic procedures, like adders, yields circuits that are more complex than the ones produced by other methods. Once a Petri net for a circuit is obtained, it can be directly translated into an implementation using circuits that have been proposed for net substructures.

Three dynamic properties of Petri Nets have direct implications on the physical implementation of the net. These properties are safeness, liveness, and conflict. The implementation of a non-safe net will produce a circuit requiring counters to keep track of the number of signals arriving to the non-safe places. The implementation of a live net is guaranteed to be fully utilized, i.e., every part of the circuit will be used. The implementation of a conflict-free net will be a circuit with no races.

In the area of fault tolerance, research has been done towards the modeling of fault phenomena in control circuits by Petri Nets [2]. Structures that can model loss, diversion, active deadlock, skew, multiple instances and tardiness of control have been developed. In this approach, the faults that can occur in any given control circuit are classified according to their effects on the circuit behavior.

The objective of this research was to determine the fault tolerance capabilities of circuits designed using Petri Nets. In order to accomplish this, a circuit implementation of an element used to implement Petri Net transitions was analyzed for fault response. The effects of these responses on the circuit containing the faulty element were then considered.

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† This research was supported entirely by the Joint Services Electronics Program under Contract F44620-76-C-0089.

The element analyzed is the c-circuit proposed by David Muller [4]. The c-circuit has been widely used in the circuit implementation of Petri Nets. This element has been mostly used in circuits utilizing simple signalling (where tokens are represented by high to low as well as low to high signal transitions), and David Misunas [3] has suggested using the c-circuit in systems utilizing reset signalling (where tokens are represented only by low to high signal transitions).

The c-circuit shown in Fig. 1, was analyzed for stuck-at type faults. This circuit can present seventeen distinguishable faults. The effects of six of these faults would produce unpredictable operation of a control circuit. The unpredictable operation results from the fact that in the presence of one of these faults, the c-circuit will operate properly for some set of input and output values, but under certain input and output conditions, the output of the circuit will follow one of the inputs. For example, if the second input to gate C is stuck at zero, the circuit operates properly for a signal value of zero at input A. For a one at input A though, the output of the circuit will follow input B.

The other eleven faults will produce an easily detectable malfunction of the control circuit. This is because under the presence of any one of these faults, the c-circuit will undergo at most one transition. For example, if input A is stuck at one, the output of the circuit will at most undergo the transition from low to high. If the control circuit is the implementation of a live, safe and conflict-free Petri Net that operates in a cyclic form, a fault of this type will cause the operation of the circuit to stop after, at most, one cycle. Thus, detection of this type of fault is easily accomplished. Fault isolation to the c-element level could also be done if there are means of determining at which point in the cycle the circuit stopped. If the c-element is implemented on an IC chip, then all the pin faults will cause the operation of the circuit to stop. This is an attractive feature, pin faults being the most common faults in digital circuits.

It was found that the use of the c-circuit for simple signalling, imposes a restriction on the structure of the Petri Nets that can be implemented. The restriction has not been graph theoretically approached, but the Petri Nets shown in Fig. 2, if implemented using c-circuits and simple signalling, will not operate properly, although the net is live, safe and conflict-free for the marking shown. Tokens (represented by signal transitions that are recorded by both c-circuits implementing the transi-

tions sharing an input place) are not actually removed when one of the transitions fires. In Figure 2, when t_1 fires, a signal transition will occur at the shared input of the circuit implementing t_2. When t_3 fires, a signal transition is received at the other input of t_2, so, t_2 will fire without waiting for t_1 to fire again.

Structures more complicated than the one shown in Figure 2 can produce the same malfunction. Thus, one structural restriction is that input places should not be shared, unless the Petri Net is a Free Choice Petri Net [4]. This restriction, however, greatly reduces the synchronization capabilities of Petri Nets.

For a circuit that would allow place sharing in simple signalling, some kind of interaction between circuits with a common input would have to exist, and some kind of memory elements would have to be included at the inputs. This would complicate the circuits and could give rise to races and hazards. Since our interest is in fault tolerance, it was decided that simple signalling should not be used, and a circuit for reset signalling was designed. The circuit shown in Figure 3, implements a transition with two input places and two output places.

The circuit in Fig. 3 requires more logic than a c-circuit and thus, can have more faults. The fault analysis of the circuit showed that regarding most pin faults, the circuit has the same fault detection characteristics of the c-circuit. I.E., most pin faults would cause the system operation to stop. Fourteen out of the sixteen distinguishable pin faults will exhibit this characteristic. The two pin faults that could produce unpredictable behavior of the system are R_I stuck-at-one and CL stuck-at-one. The stuck-at-one fault in R_I will produce the desired effect if a restriction is imposed on the Petri Net structure. The restriction is that no transition should share all its input places. This requirement is not as restrictive as the one believed to be imposed by c-elements in simple signalling. A stuck-at-one in CL could result in the circuit being wrongly initialized, producing a system malfunction. For a cyclic control circuit implementing a live, safe and conflict-free Petri Net, this fault can be detected and perhaps even marked out. If such a system is forced to undergo it's cycle once, the faulty element will either stop the cycle, or will be properly initialized when the cycle is over.

Petri Nets structures that will model each of the faults that can be present in the circuit (except for four), have also been developed as part of the research.

Control circuits designed using Petri Nets require more hardware than circuits designed by other techniques, but they seem to have more attractive fault tolerant capabilities. The advantage of Petri Nets is that the fault tolerance features of the designed circuits are intrinsic to the design method, that is, the designer does not have to include them in the design.

Another approach that has been taken to implement Petri Nets uses an array of diodes [1]. These circuits seem to be more suited for place sharing, and apparently the method imposes less restrictions on the nets that can be implemented. Research on the fault tolerant capabilities of these circuits will be done.

Another area where research will be done is simulation of functional devices. The possibility of using Petri Nets as a description tool in the simulation of functional devices will be studied.

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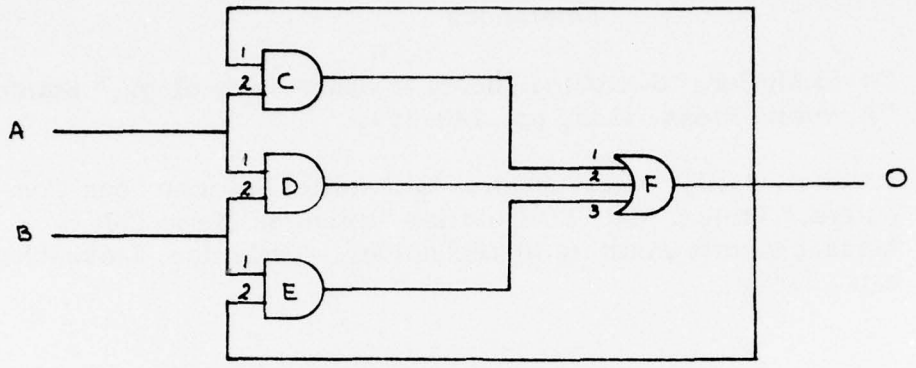
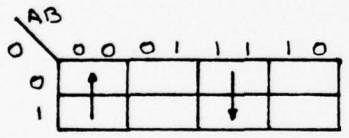
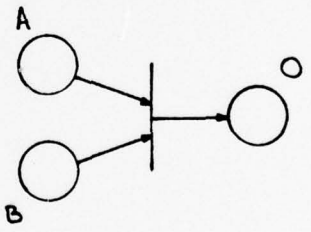




Transition Table



Petri Net

Figure 1. C-Circuit.

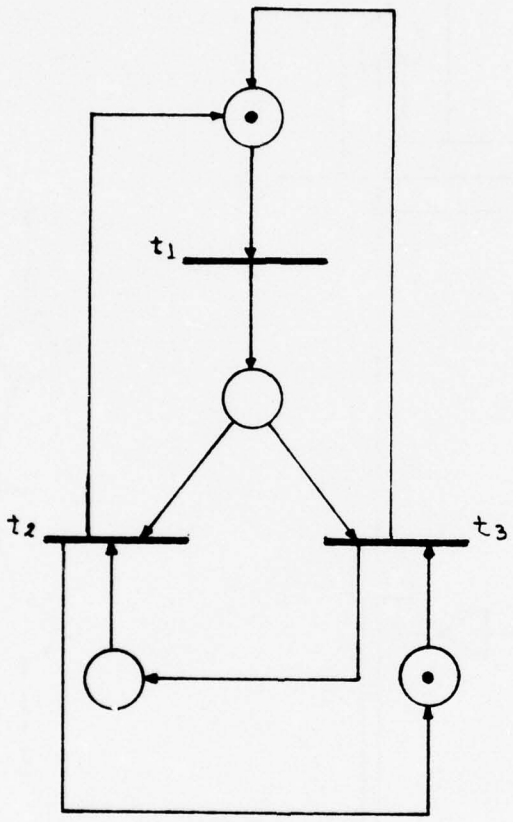
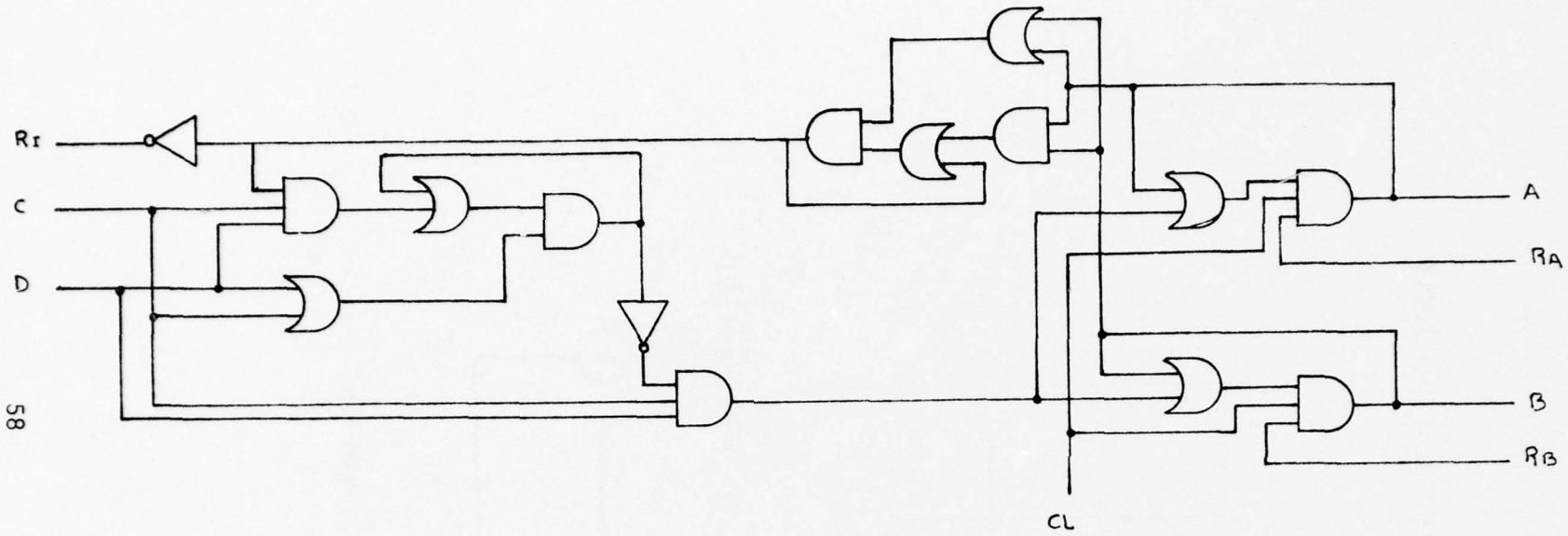


Figure 2. Petri Net.



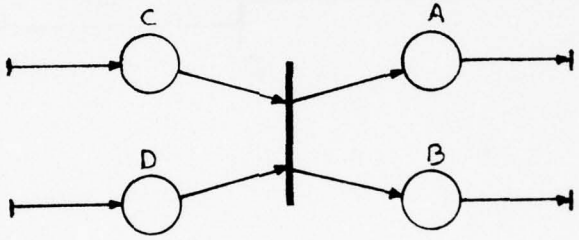


Figure 3. Implementation Of Transition For Reset-Signalling.

E. CONCURRENT SYSTEM SYNTHESIS†

Professor Tilak Agerwala and Yong-chai Choed-amphai

Concurrent systems, characterized by multiple loci of control, are extremely complex and difficult to analyze. The primary objective of this research is to formulate procedures for the systematic synthesis of systems with known properties so that no subsequent analysis is required, or of systems whose behavior is easily verifiable. The synthesis procedures should allow the use of hierarchic integration (bottom-up) techniques as well as structural decomposition (top-down) techniques.

The basic approach was to use the Petri net model [1,2]. This model has proven to be a convenient tool for the representation and study of concurrent systems. Techniques were considered for synthesizing Petri nets with known properties.

It is assumed here that the reader is familiar with the Petri net model. Petri nets, though known to be good models for concurrent systems, are difficult to analyze. The conventional practice is to design a net and then analyze its properties. A number of iterations of design and analysis may be required before a "correct" net is obtained. This process can be quite expensive. In [3] a Petri net is analyzed by obtaining an incidence matrix and solving a system of linear equations to obtain invariants. An invariant is a minimum set of places such that the sum of tokens in the places in the set remains constant. These invariants are then used to prove or assist in proving the correctness of Petri nets.

In contrast, we have taken a synthesis approach. A net is constructed from a basic building block according to a construction rule. The final net is guaranteed to have the important property of boundedness. (Boundedness means that each place will always have less than N tokens where N is an a priori known value.) This property is essential for implementation. In addition, all invariants of the net are obtained as by-products from the synthesis process. The results are summarized below. Proofs of theorems have been omitted.

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† This research was supported entirely by the Joint Services Electronics Program under Contract F44620-76-C-0089.

Definition 1: Given a net $N_1 = (P_1, T_1, A_1)$ (P_1 is the set of places, T_1 is the set of transitions, A_1 is the set of arcs) where p_1, p_0 are any two places of N_1. If N_1 is modified to $N_2 = (P_2, T_2, A_2)$ such that:

$$P_2 = \left[P_1 - \{p_1, p_0\}\right] \cup \{p\} \text{ where } p \notin P_1$$

$$T_2 = T_1 \text{ and}$$

$$A_2 = \left[A_1 - \{(p_i, t) \mid i = 1, 2\} - \{(t, p_i) \mid i = 1, 2\}\right] \cup \{(p, t) \mid (p_i, t) \in A_1, i = 1, 2\} \cup \{(t, p) \mid (t, p_i) \in A_1, i = 1, 2\}$$

then p_1 and p_2 are said to have been merged to p to form a new net N_2.

Synthesis basics. Let p_1 and p_2 be any two places of a Petri net $N_1 = (P_1, T_1, A_1)$ such that:

1) each of them is in some invariant of N_1,
2) for all $t \in T_1$, $(p_1, t) \in A_1 \Rightarrow (p_2, t) \notin A_1$ and

$$(t, p_1) \in A_1 \Rightarrow (t, p_2) \notin A_1$$

Let $I_{11}, I_{12}, \ldots I_{1n}$ and $I_{21}, I_{22}, \ldots I_{2m}$ be invariants such that $p_1 \in I_{1j}$, $1 \leq j \leq n$ and $p_2 \in I_{2k}$, $1 \leq k \leq m$.

If p_1 and p_2 are merged to p_3, and the new net is N_2, then

Theorem 1: If I is an invariant of N_1 containing p_1 and/or p_2, then I is not an invariant of N_2.

Theorem 2: The set of all invariants of N_2 not containing p_3 is identical to the set of invariants of N_1 not containing p_1 and/or p_2.

Theorem 3: All invariants of N_2 containing p_3 are obtained as follows:

For every pair of invariants I_{1i} and I_{2j} such that

$$I_{1i} \cap I_{2j} = \emptyset \text{ or } I_{1i} = I_{2j},$$

the set $I_{1i} \cup I_{2j} \cup \{p_3\} - \{p_1, p_2\}$ is an invariant of N_2 provided that no other invariant of N_2 is its proper subset.

The Synthesis Procedure. The synthesis process is as follows:

1. Begin with a building block.
2. Bring in another building block or merge two places. The merging can be performed only if every place will still be contained in at least one invariant after the merging.
3. If the required net is completed then stop; else go to step 2.

Checking for the merging requirement in step 2 can be done using theorem 1 to 3. A building block is any Petri net all of whose invariants are known and every place is in some invariant.

Theorem 4: The Petri nets built according to the synthesis procedure are bounded.

Theorem 5: The class of nets synthesized is equivalent to the class of bounded nets. (The definition of equivalence is taken from [1]).

Example

A very simple example is presented to illustrate the procedure. Two "consumer" processes are to be modeled. The consumers should not consume at the same time.

The consumer processes are first synthesized as shown in Fig. 1a. t_2 and t_4 represent the process of consuming. This synthesis can be done using some basic building blocks. The invariants for the net in Fig. 1a are:

$$I_1 = \{p_4, p_5\}$$

$$I_2 = \{p_6, p_7\}$$

$$I_3 = \{p_1\}$$

$$I_4 = \{p_2\}$$

p_1 and p_2 are then merged to get the net in Fig. 1b. The invariants are:

$$I_1 = \{p_4, p_5\}$$

$$I_2 = \{p_6, p_7\}$$

$$I_3 = \{p_3\}$$

Since each place is in some invariant, the net is bounded for any initial marking. Initially, assume a single token is placed in each of the places p_4, p_6 and p_3. Since t_2 and t_4 both have an input place in the same invariant ($\{p_3\}$), and since the sum of the tokens in the places of this invariant is 1, t_2 and t_4 fire in a mutually exclusive manner. Therefore, the two consumers cannot consume at the same time. A knowledge of the three invariants can also be used to prove the absences of deadlock.

Plans for the Next Period

1. Further rules for bottom-up synthesis will be considered. The top-down approach will also be considered, i.e., how can transitions be expanded into nets so that certain properties are preserved.

2. The limitations of the use of invariants in proving the correctness of nets will be investigated.

3. Using the formal rules, an attempt will be made to provide guidelines for synthesizing

- parallel programs (operating systems)
- data flow programs
- software for distributed processor systems.

The overall aim is to preserve certain properties during synthesis so that system behavior is easily verifiable.

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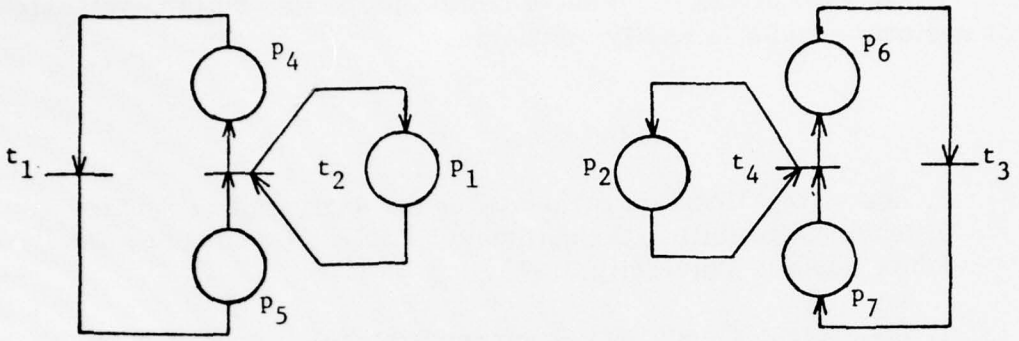

Figure 1a. Before Merging of p_1 and p_2.

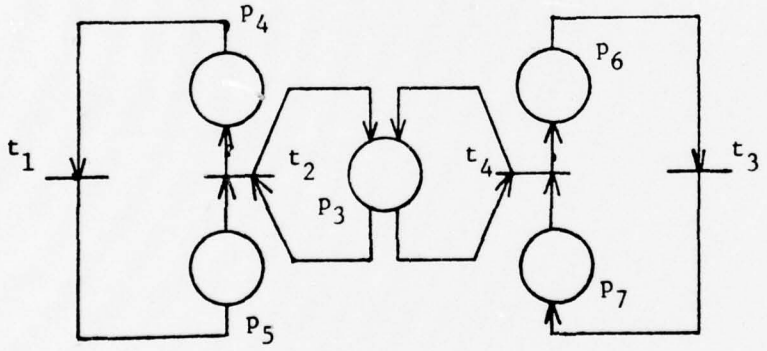

Figure 1b. After Merging of p_1 and p_2.

F. COMMUNICATION IN CONCURRENT SYSTEMS †

Professor Tilak Agerwala

Well developed theories of computation and numberous system analysis and design techniques have allowed the construction of high performance, essentially serial computing devices. Speed, efficiency, and fault tolerance requirements, however, indicated that the notion of concurrency or parallelism be exploited in computing systems. Rapidly dropping hardware costs made it feasible to build systems consisting of interconnections of numerous autonomous computing elements. Such systems, in general have not performed even close to original expectations. One reason is insufficient emphasis on the important role of communication in such systems and its relationship to computation. The prime objective of this research is to provide a framework in which communication aspects can be formally studied. Another objective was to investigate techniques for the synchronization of processes in a multiprogrammed or multiprocessor system.

The approach to studying communication aspects was basically to "start small." A simplistic model of communication was developed and various situations were analyzed using this model, to provide some insight into the role of communication in concurrent systems and its relationship to computation.

A simple model of communication and a measure of communication complexity was proposed. This model consists of a graph where each node consists of a processor with some local memory. The processor is capable of performing simple arithmetic/logical operations according to a program stored in memory or wired in. The arcs of the graph represent links along which data, signals, etc. are transmitted from one node to another. Everything occurring inside the node is termed computation. Activity on the arcs is termed communication. The total number of primitive operations (summed over all node) is defined as "computation complexity" and the total number of arcs is defined as "communication complexity."

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†This research was supported entirely by the Joint Services Electronics Program under Contract F44620-76-C-0089.

It is assumed that each algorithm statement contains sufficient information to determine the kind of system graph it will execute fastest on. The complexity of the graph then gives the complexity of the algorithm. The communication provided by a particular hardware configuration can be determined by modeling it as a graph.

The problems listed below were analyzed using this simple model for communication:

(1) Finding the maximum of a sequence of N numbers

(2) Computing the Discrete Fourier Transform

(3) Permuting data in a SIMD machine

(4) Sorting a sequence of N numbers

(5) Communicating in a computer network

(6) Determining the minimum spanning trace of a network

This exercise illustrated the following:

(1) Communication plays a critical role in distributed computing systems

(2) Systems with different amounts of computation and communication can be designed for performing the same overall task

(3) Computation/communication complexity trade-offs are possible

(4) It may be possible to increase speed of execution by going to higher communication complexity

(5) Given current technology, minimizing execution time on a sequential machine or minimizing hardware may not be appropriate.

For details, the reader is referred to [1]. The work on implementation was primarily a continuation of research conducted during 1974-1975 (supported by U.S. Atomic Energy Commission under contract AT(11-1-3288)). New synchronization primitives were proposed and shown to be complete: they can represent any desired interaction between processes without the use of conditionals. The usefulness of the primitives was illustrated and disadvantages of existing synchronizing mechanisms pointed out. A straightforward but efficient implementation of the primitives was also obtained.

For details, the reader is referred to [2].

The following will be undertaken:

(1) Development of a theoretical foundation for studying communication in parallel systems.

   (a) The model obtained thus far is quite simplistic. It does not adequately cover all important aspects. (Ex. processor memory communication within a node has not been considered). A more sophisticated model will be developed.

   (b) The measure of communication complexity is quite primitive. Other measures such as link capacities, number of transfers, fan-in/fan-out, etc. will be considered and a more realistic model developed.

(2) Application of theoretical framework to the design and analysis of concurrent systems.

   (a) Selected architectures and algorithms will be analyzed using the theoretical framework.

   (b) Existing building blocks such as microprocessors will be evaluated to determine the complexity of communication they can realistically be expected to handle. Architectural features to enhance communication will be studied.

(c) New approaches for algorithm analysis will be considered.

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G. SOFTWARE VERIFICATION †

Professor R. T. Yeh

Our primary activity during the past twelve months was concentrated on programming methodology, especially in the area of program verification. Two distinct parts of our investigations are reported here.

(1) Verification of non-deterministic programs by predicate transformation. In this work, we present a methodology for the verification of both deterministic and non-deterministic programs. Our method is based on the concept of predicate transformer introduced by Dijkstra. The predicate transformer is used to define formal semantics of programs by a mapping which transforms a set of states after the execution of a program, to the set of all possible states before the execution of the same program. Thus, the difference between the concept of determinism and non-determinism loses its significance in this semantic concept. The focus is on the nature of the computation; and hence, the concept of iteration, not how the program iterates, is of concern in the current context.

By the very nature of the semantic definition using predicate transformers, it is implicitly assumed in our method that the termination property of a program is an inherent property of the algorithm that realizes the given program. Furthermore, termination and consistency can be handled by the same modus operandi. These points are illustrated by a number of examples.

In this work, the main results were the method for generating the weakest preconditions. We have investigated two methods: by generation of a sequence of approximations of the final predicate and, by solving a solution for recursive equation. These two techniques indeed can be used to comp-

† This research was supported in part by the Joint Services Electronics Program under Contract F44620-76-C-0089 and in part by the National Science Foundation.

liment each other in locating the loop invariant. The generation of successive turns will provide a guideline in obtaining a candidate, and the recursive equation provides a test for checking the adequacy of the candidate. Therefore, these two techniques are useful additions to any verification system based on inductive insertion method. The impact of the work here is that we treat total correctness instead of partial correctness. On the other hand, from the practical viewpoint, a basic limitation is imposed by our method by the exploding complexity for finding the weakest precondition.

(2) In this part, our investigation is centered in the study of the nature of verification processes. We have considered the inductive mechanisms for five techniques of verifying interactive/recursive program structures: inductive assertion, predicate transformers, subgoal induction, computation induction and structure induction. We have discovered that all five techniques can be justified by a single theorem of inductive proof technique. We have also shown that all five techniques face exactly the same problem of finding properties that will carry an induction. Such properties, I refer to as "inductive set". We have proven that in the inductive set, all five techniques are easily related to one another and that a program proof of any one technique can be easily converted to a proof of any one of the other techniques. We were able to then conclude the computer programs simply are inductive definitions of the functions they compute. Induction, therefore, is the only method by which they can be proved and hence, the problem of induction is therefore unavoidable. It seems that the same method is applicable to cahracterize termination proofs and we are working on that prospect.

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IV. ELECTRONIC CONTROLS

(IV. ELECTRONIC CONTROLS)

A. ELECTRONIC CONTROL SYSTEMS--RESEARCH IN ESTIMATION AND ANALYSIS OF NONLINEAR STOCHASTIC SYSTEMS †

Professor Steven I. Marcus

The objective of this research is the development of a theory for the design and analysis of nonlinear stochastic dynamical systems. These problems are of considerable importance in many areas of communications, control, guidance, and tracking. Optimal estimators previously have been derived for very general classes of nonlinear systems. However, the optimal estimator requires, in general, an infinite dimensional computation to generate the conditional mean of the system state given the past noisy observations. This computation involves either the solution of a stochastic partial differential equation for the conditional density or an infinite dimensional system of coupled ordinary stochastic differential equations for the moments of this density. Hence, approximations must be made for practical implementation.

One of the major research activities undertaken in the past year under the partial support of this grant is an investigation of the use of the inherent structure of particular subclasses of nonlinear stochastic systems in order to design high-performance, easily implementable suboptimal estimators for these systems. In particular, the tools of harmonic analysis on Lie groups and homogeneous spaces have been used to design suboptimal estimators for nonlinear systems whose state evolves on a compact Lie group or homogeneous space, such as the n-sphere [2], [4], [7]-[9]. These models have applications in phase tracking and demodulation, satellite tracking, and rigid body orientation estimation.

The approach taken in this research consists of the truncation of the infinite set of coupled equations for the moments of the conditional density of the state, by means of an assumed density approximation. That is, the conditional density of the state is expanded in the appropriate harmonic expansion (e.g., Fourier series on the circle or spherical harmonics

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on the sphere). However, the higher order coefficients are not merely set equal to zero, for it has been shown that this does not result in good performance. Instead, it is assumed that the conditional density is a so-called "normal" density on the particular Lie group or homogeneous space; these densities have many of the same properties as the Gaussian density on $\mathbb{R}^n$, and depend on a small finite number of parameters. This assumption effectively truncates the infinite dimensional optimal estimator by expressing higher-order moments in terms of lower-order ones, without eliminating the higher-order moments (e.g., the high-frequency components in a Fourier series expansion). This approach has been highly successful, as the following results indicate.

In [2], estimation on the 2-sphere S^2 is considered. This problem is motivated by the desire to track a satellite in a spherical orbit about a celestial body, where it is assumed that the orbit is perturbed by random effects which can be modeled as Gaussian white noise. In this case, a reasonable model for the evolution of the position $x(t)$ of the satellite at time t is that of a stochastic bilinear differential equation driven by Gaussian white noise; the observations are assumed to be linear observations of $x(t)$ corrupted by additive Gaussian white noise. The optimal estimator and the suboptimal estimator resulting from the normal assumed density approximation on S^2 are derived. Monte Carlo computer simulations, reported in [9], show that this suboptimal estimator performs at least as well, under a variety of parametric conditions, as the extended Kalman filter and the Gustafson-Speyer state-dependent noise filter, and with comparable or fewer computations. In fact, the particular estimator simulated in [9] is computationally quite simple, having been truncated after the first-order moments of the conditional density (this is called the first order filter).

In [4], the corresponding results for bilinear systems evolving on compact Lie groups are presented; the concepts of group representation theory are utilized in the analysis and in the derivation of the normal assumed density approximation on a compact Lie group. Both optimal and suboptimal estimators are studied. This class of problems is motivated by the problem of estimating the orientation of a rotating rigid body; the state of the system is a direction cosine matrix, which evolves on the special orthogonal Lie group $SO(3)$.

The methods discussed here are successfully applied to an optical phase tracking problem in [7]. In this problem, the state of the system is the phase $\theta(t)$, and $\sin\theta(t)$ is used to modulate the intensity of a coherent light source, such as a laser, which is pointed at a remote receiver. As opposed to the previous problems in which the observations consisted of nonlinear functions of the state corrupted by additive white noise, the observation in this problem consists of the output of a photodetector--a doubly stochastic Poisson process with rate modulated by $\sin\theta(t)$. The objective is to estimate $\theta(t)$ given the past observations of the photodetector. The state (i.e., the phase $\theta(t)$) evolves on the circle, so Fourier series and the folded normal density are the appropriate tools for designing the normal assumed density suboptimal estimator. Monte Carlo computer simulations have shown that the first order filter designed by this technique performs better at low frequencies and comparably or slightly worse at high frequencies, than the previously used "quasi-optimum" estimator of Snyder for this problem. The phase estimation problem in which both jump process observations and nonlinear observations with additive white noise are available, is considered in [8].

A major effort has been undertaken during the past year to investigate the properties of nonlinear stochastic systems driven by multiplicative Poisson white noise, with the eventual goal of solving estimation and control problems. Such systems have many applications, including that of modeling a satellite subject to random micrometeorite collisions. In [1] and [5], the analysis of linear systems with multiplicative Poisson white noise is considered. The stochastic calculus of McShane is extended to this case by means of an injection procedure which is similar to that of McKean. Other properties of such systems are studied, and moment equations and necessary and sufficient conditions for stochastic stability are derived. These results are extended considerably in [3] and [6] to general nonlinear systems with Poisson white noise. It is proved that this extension possesses the same desirable properties as McShane's calculus. This work represents a considerable step in the direction of providing a unified calculus which applies to a large class of noise processes.

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B. RESEARCH IN LARGE SCALE SYSTEMS AND DESIGN TECHNIQUES †

Professor Baxter F. Womack and Associates‡

Three problems have been investigated in the area of large scale systems theory. In [1], three different configurations of dynamic multiple-connected subsystems are considered. The general state variable equations for circular, polar, and circular-polar configurations of n subsystems are given. For a specific class of subsystems and $n = 4$, complete input-output relations are developed. System stability and controllability are investigated. In [2], properties of the matrix Lyapunov equation are developed using spectral norms to establish upper and lower bounds of eigenvalues that guarantee a positive definite solution of the Lyapunov equation. This work is continuing and will be useful in designing large scale systems created by connected subsystems. In [3], a new numerical calculation method is treated for solving simultaneous ordinary differential equations of higher order as initial value problems. The concept of a diagonalized modal property is introduced to achieve necessary simplification.

New design techniques for control systems are being investigated. In [4], it is demonstrated that a system response can be improved by means of a multi-valued switching circuit that is controlled by measuring on-line system variables and analogous on-line Nyquist points. Other research in progress in the design area includes (a) nonlinear synthesis procedures in the frequency domain when time domain tolerances are specified, and (b) nonrecursive digital filter design specifications, architecture, and limitations.

Sensitivity theory is being developed and utilized in several ways in continuing research projects. In one project, time domain sensitivity functions are being used to optimize a large dimensional, nonlinear dynamic system. In two other projects, new and more useful formulations of sensitivity functions are being sought which can be used on (a) systems with multiple eigenvalues, and (b) adaptive systems with multiple inputs and outputs.

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New and novel methods of characterizing and solving control problems are continually sought. One effort in this direction is indicated in [5] and [6], where coordinate transformations of parameterized arcs have enabled the invariative structure inherent in the Hamilton and Lagrange equations to be exposed by means of tensor analysis. A continuing goal of this research is to utilize tensors and extensors to characterize problems having multiple performance indices. Another effort focuses on understanding human tasks as an intermediate step in formulation of new control strategies for broader classes of control problems. In [7], a model is postulated and tested to predict major shifts in the search strategy of human subjects analyzing multimodal surfaces. In [8], a detailed investigation of human search experiments reveals that the human concept formation of the multimodal optimum point has five subconcepts, namely a point-segment concept, line-segment concept, plane-segment concept, local-surface concept, and global-surface concept.

‡Associates: V.M. Levykin, J.J. Montemayor, Sadao Azuma, Y. Tjandra, D.O. Nilsson, C.R. Browning, T. Nagooka, and M. Oda.

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C. RECENT RESULTS IN LARGE SCALE APPROXIMATIONS OF POINT CONTROLLED DISTRIBUTED SYSTEMS †

Professor R. H. Flake

A new numerical method for optimal point control of elliptic distributed parameter systems has been developed under the Joint Services Electronics Program support and applied in several studies [1, 6]. In these studies, a new efficient large scale system numerical solution technique based on multiple shooting [3, 4, 9], called extended multiple shooting (EMS), was developed for solving mixed boundary value problems for linear and semi-linear elliptic systems defined on $\mathbb{R}^1$ and irregular regions in $\mathbb{R}^2$. This new numerical approach may be employed with large scale finite difference or finite element approximations for the operator. The method entails an order reducing feature in which the original point control problem is transformed into an equivalent problem possessing much fewer unknowns. This feature has been demonstrated for systems involving discretization of up to 2,000 grid points which were reduced to equivalent problems containing around fifty variables [6]. The resultant convergence rate for the boundary value problem solution was almost three times as fast as the successive over-relaxation technique in a large estuarine modelling problem [8]. The optimal parametric point controls were obtained by applying the Goldfarb's search algorithm. These earlier applied studies under the National Science Foundation sponsorship involved the determination of optimal waste treatment plant capacities for Jamaica Bay, a small estuary in New York [5] and for Corpus Christi Bay, a large estuary on the Gulf Coast of Texas [8]. Control and state variable inequality constraints were employed to impose realistic waste treatment plant characteristics and water quality standards in the analyses. It was apparent, in both studies, that minimum waste treatment capacities for satisfying water quality standards in the estuaries could be achieved at about one-third the capital and operating costs required by the uniform plant treatment policies usually espoused by the regulatory agencies.

A brief problem statement for optimal point control of elliptic systems and the method of solution are outlined below.

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Optimal Point Control for Elliptic Systems

The solutions of optimization problems have been obtained for several elliptic distributed parameter systems which have controls applied pointwise in the problem domain. A brief problem statement follows:

Find $\alpha^* \in S$ such that

$$\inf_{\alpha \in S} J(\alpha) = \inf_{\alpha} \sum_{j=1}^{N_\alpha} f(\alpha_j) \tag{1}$$

subject to state equations, which for a linear second order elliptic system are:

$$\frac{\partial}{\partial x}\left(E_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y \frac{\partial C}{\partial y}\right) - \frac{\partial}{\partial x}(uC) - \frac{\partial}{\partial y}(vC) - K(x,y)\, C$$

$$= \sum_{j=1}^{N_\alpha} h(\alpha_j)\, \delta(x - x_j,\ y - y_j) \quad , \quad (x,y) \in \Omega \subset \mathbb{R}^2 \tag{2}$$

with boundary conditions

$$\gamma C(x,y) + \mu \frac{\partial C(x,y)}{\partial n} = 0 \quad , \quad (x,y) \in \partial\Omega$$

where

$$|\gamma| + |\mu| = 1$$

and state variable inequality constraints

$$C(x,y) \leq g(x,y) \quad , \quad (x,y) \in \Omega \qquad (3)$$

where the set S is the admissible control parameter set which is a convex subset of $\mathbb{R}^{N_\alpha}$

$$f(\cdot) \in \mathbb{C}^2 \; ; \; g(\cdot,\cdot), h(\cdot,\cdot) \in \mathbb{C}^{2,2(\Omega)}, E_x(\cdot,\cdot), E_y(\cdot,\cdot),$$

$$u(\cdot,\cdot), v(\cdot,\cdot) \in \mathbb{C}^{1,1}(\Omega)$$

$\delta(x,y)$ is the delta function at $x=0$, $y=0$, E_x and $E_y > 0$, $\forall (x,y) \in \Omega$.

The above problem is reformulated in terms of a perturbation parameter vector $\beta = (\alpha - \alpha_0)$ and the sensitivity function $\frac{\partial C}{\partial x} = S(x,y)$ where h is assumed to be a linear function of α.

Solution Method

The optimization problem defined by (1), (2), and (3), has a unique solution and is equivalent to the problem.

Find $\beta \in \boldsymbol{\beta}$ which minimizes

$$J(\beta) = \sum_{j=1}^{N_\alpha} f(\beta_j)$$

subject to

$$S_\alpha(x,y)\,\beta \le g(x,y) - \tilde{C}(x,y) \quad , \quad (x,y) \in \Omega$$

where, $\beta \in \boldsymbol{\beta}$, is the constraint set and $\tilde{C}(x,y)$ is the solution of (2) with $\alpha = \alpha_0$

where $S_\alpha(x,y)$ is the sensitivity function of the state to the control parameters α.

This sensitivity function satisfies the boundary value problem

$$\frac{\partial}{\partial x}\left(E_x \frac{\partial S_\alpha}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y \frac{\partial S_\alpha}{\partial y}\right) - \frac{\partial (u S_\alpha)}{\partial x} - \frac{\partial (v S)_\alpha}{\partial y} - K(x,y)S$$

$$= \sum_{j=1}^{N_\alpha} \frac{\partial h}{\partial \alpha_j}\, \delta(x - x_j,\, y - y_j) \quad , \quad (x,y) \in \Omega \subset \mathbb{R}^2$$

with boundary conditions

$$\gamma S(x,y) + \mu \frac{\partial S(x,y)}{\partial n} = 0 \quad , \quad (x,y) \in \partial\Omega \ .$$

The proof of the equivalence of this alternative formulation with the original problem is given in [7]. This result means that the original formulation is equivalent to a constrained minimization problem which may be solved for discretized problems by non-linear programming methods. This approach requires both the solution of the state and the state sensitivity equations.

The EMS method is based on the equivalence between the solution of the boundary value problem and an initial value problem. The equivalence is expressed by the following statement:

> The unique solution to the boundary value problem (2) is equivalent to the solution of a Cauchy problem defined by the same differential operator, with boundary values and derivatives on a part of the boundary, $\partial\Omega_p$, such that the domain of dependence of the initial values contains Ω and all boundary conditions are satisfied on $\partial\Omega_g = \{ (x,y) \in \partial\Omega \notin \partial\Omega_p \}$.

This statement may be verified by an application of the properties of the solutions to (1). The extended shooting technique is a method which can be used to calculate the unknown initial value for the equivalent Cauchy problem. The resulting Cauchy problem is not well-posed, in general, as can be verified from Hadamaard's well posedness condition [2]. In practical problems, this condition manifests itself by divergence of the algorithms [3] due to numerical ill-conditioning. This problem is alleviated by the EMS method which decomposes the original domain Ω into a net of N_Ω subregions Ω_j such that

$$\Omega = \bigcup_{j=1}^{N_\Omega} \Omega_j \cup \left[\bigcup_{j,k}^{N_\Omega} \partial\Omega_{jk} \right]$$

where

$$\partial\Omega_{jk} \neq \emptyset \quad \text{if} \quad \bar{\Omega}_j \cap \bar{\Omega}_k \neq \emptyset$$

and is based on the following result.

> The unique solution to the boundary value problem (2) is equivalent to the solution of a multi-boundary value problem defined on Ω_j, $\{j = 1,2,\ldots,N_\Omega\}$ satisfying the same operator of (2), the original boundary conditions and additional conditions $C(x,y) \in \mathcal{C}^{2,1}(\partial\Omega_{jk})$.

The proof of this statement follows from the properties of the solutions to the system state equations and from the previous statement on equivalence. The multiple boundary value problems defined with respect to the subregions indicated above may be solved by shooting. The resulting technique is referred to as the EMS method. EMS numerical algorithms have been employed in the modelling, analysis and optimal control of elliptic distributed parameter systems. The discrete implementation of the EMS technique involves integrating the operator equations by means of numerical integration and assuming arbitrary values for unspecified initial values at the subregion boundaries. A Newton type iteration procedure is then employed to compute a solution which satisfies the boundary conditions at the final points. The domain of dependence of each initial value problem was selected to minimize the ill-conditioning caused by growth of the trial solutions. Large scale approximations to the elliptic problems of the class considered have been solved by this method.

In [5], we used the EMS technique to solve the multi-point boundary value problems satisfied by several water quality variables for Jamaica Bay, New York. A numerical integrator for ordinary differential equations was used for integrating the operators. The problem, which had four point controllers, was decomposed into eighteen spatial subregions. The multiple shooting algorithm reduced the error in the Newton iteration for the correct initial values to 10^{-10} in two iterations.

In [6], a multiple shooting technique was used to integrate the dispersion-advection equations for Corpus Christi Bay, a large, two-dimension, estuary in Texas. In contrast to the previous problem, a two-dimensional integrator was derived from the five point finite difference approximations [10] for the operator. Altogether, 269 mesh points were involved in the problem along with twenty-three controllable inputs. The subregions employed in the shooting algorithm required thirty-two initial values to define an EMS formulation consistent with the original boundary value problem. The Newton iterations for satisfying the boundary conditions converged in about three iterations. The method was found to be almost three times as fast as an earlier solution technique applied to this problem that was equivalent to the standard successive over-relaxation method.

In [1], the EMS method was employed to solve a discrete-time continuous space approximation for parabolic distributed systems. High accuracy spatial approximations were achieved with algorithms requiring less than twenty initial values. These studies indicate that the EMS method has excellent convergence characteristics and permits the computation of realistic large scale approximations for elliptic and parabolic distributed systems.

Several of the studies mentioned above also involved the computation of optimal point controls for large scale elliptic problems. In each case, the sensitivity equations for the problem relative to the controls were computed by the EMS method. The equivalent formulation then reduces to mathematical programming, which is defined by a non-linear cost function subject to linear inequality constraints and bounds.

These recent results demonstrate that the EMS approach is a powerful method for solving large scale approximations to elliptic distributed parameter systems. In future investigations under JSEP sponsorship, we propose detailed, theoretical studies of solutions for parabolic problems as well as the computation of open loop and closed loop controls for parabolic problems with point controls. The EMS technique should provide a powerful tool for solving the optimality equations for parabolic systems. It is also important to note that the numerical state decoupling and order reduction characteristics of the EMS technique is of a different nature from those used in the aggregation and other contemporary large scale methods. Various current techniques of decentralized control and other suboptimal policies could also be combined with the resulting high

resolution EMS models to study very large problems.

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V. PLASMA AND QUANTUM ELECTRONICS

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(V. PLASMA AND QUANTUM ELECTRONICS)

A. BISPECTRAL ANALYSIS OF NONLINEAR WAVE INTERACTION DATA †

Professor Edward J. Powers and Y. C. Kim

1. INTRODUCTION

In the past we have developed, partially under JSEP sponsorship, techniques which have proven useful in experimentally analyzing and interpreting fluctuation data associated with waves and instabilities [1,2]. The approach is to digitize the fluctuation data of interest and then from the corresponding raw time series data compute various spectral and statistical functions of interest. Of particular interest is the fact that digital spectral analysis based on FFT techniques is capable of resolving a fluctuation spectrum into a linear superposition of the various component waves. In particular, one can simultaneously determine the amplitude, frequency, wavenumber, and coherence of each wave present in a fluctuation spectrum. This phase of the work is now supported by the National Aeronautics and Space Administration.

In analyzing fluctuation data characterized by nonlinear or parametric wave-wave interactions, "linear" spectral analysis techniques are of obviously limited value. Thus, during the past year we have turned our attention to the problem of developing procedures that are suitable for analyzing "nonlinear data." In particular, higher-order spectral techniques are required to analyze such data. For example, for a system which is quadratically nonlinear, the two-dimensional frequency spectrum, the bispectrum, is the appropriate spectral quantity to consider.

2. THE BISPECTRUM

The bispectrum is best introduced by way of application to a specific problem. Suppose that some fluctuating signal has been digitized and that classical "linear" spectral analysis indicates waves present at frequencies ω_1, ω_2, and $\omega_1 \pm \omega_2$ with wavenumbers k_1, k_2, and $k_1 \pm k_2$, respectively. The fact that waves exist at sum and difference frequencies suggests that a nonlinear interaction has taken place. However, if all the waves are normal modes of a system, there exists the

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possibility that the sum and difference frequency waves were spontaneously excited. Thus, the first question we considered was how does one discriminate between spontaneously excited waves and those which are coupled through some nonlinear or parametric interaction? The second question concerns the possibility of experimentally determining the complex coupling or interaction coefficient from the experimental data.

We consider the discrimination problem first by introducing the bispectrum [3] and reviewing some of its properties. Mathematically, the bispectrum $B(\omega_1, \omega_2)$ corresponds to two-dimensional Fourier transform of a second-order correlation $c(\tau_1, \tau_2) = E[x(t)x(t + \tau_1)x(t + \tau_2)]$ where E denotes an expected value. The fluctuating quantity x(t) is assumed to be statistically stationary. Since the second-order correlation is defined in terms of a third-order product moment, the bispectrum is a mean cube spectral density. That is, $B(\omega_1, \omega_2)d\omega_1 d\omega_2$ is the contribution to the mean cube $E[x^3]$ of those spectral components lying in the ω_1 to $\omega_1 + d\omega_1$ and ω_2 to $\omega_2 + d\omega_2$ intervals in the $\omega_1 \omega_2$ - plane. Although the bispectrum is equivalent to a two-dimensional Fourier transform of $c(\tau_1, \tau_2)$, it may also be written as

$$B(\omega_1, \omega_2) = \frac{1}{T} E\left[X(\omega_1)X(\omega_2)X^*(\omega)\right] \; ; \quad \omega = \omega_1 \pm \omega_2 \qquad (1)$$

where $X(\omega)$ is the Fourier transform of x(t), T is the time duration of the x(t) signal and the asterisk represents a complex conjugate [4].

Examination of Eq. (1) clearly indicates that the bispectrum will be zero unless the following two conditions are met:

1) Waves must be present at the frequencies ω_1, ω_2, and $\omega_1 \pm \omega_2$.

2) A phase coherence, or phase consistency, must be present between the waves mentioned in 1).

In more physical terms, we note that if waves are present at ω_1, ω_2, and $\omega_1 \pm \omega_3$, then condition 1) is satisfied. Suppose, however, that these waves are spontaneously excited normal modes of the system. In this case each wave will be characterized by statistically independent random phases, and, thus, when the statistical averaging indicated by the expectation operator is carried out, the bispectrum will ideally take a zero

value. On the other hand, if the sum and difference frequency waves were generated through some nonlinear or parametric interaction, then the respective phases of the waves would no longer be statistically independent but rather a phase coherence would exist. As a result of this phase coherence, the statistical averaging will not lead to a zero value of the bispectrum. Thus, our approach in attacking the problem of discriminating between coupled waves and those which are spontaneously excited is based on the facts that coupled waves are phase coherent and that the bispectrum may be used to measure the degree of phase coherence. Strictly speaking, a normalized bispectrum, known as the bicoherence spectrum, is used to measure the degree of phase coherence.

3. THE BICOHERENCE SPECTRUM

The bicoherence spectrum is defined as

$$b(\omega_1, \omega_2) = \frac{1}{T^{\frac{1}{2}}} \frac{|B(\omega_1, \omega_2)|}{\left[P(\omega_1)P(\omega_2)P(\omega)\right]^{\frac{1}{2}}} \; ; \quad \omega = \omega_1 \pm \omega_2 \tag{2}$$

where $P(\omega) = \frac{1}{T} E\left[X(\omega)X^*(\omega)\right]$ is the auto-power spectrum. The statistical properties of the bicoherence spectrum may be interpreted as follows. Suppose that between random variables $X(\omega_1)$, $X(\omega_2)$ and $X(\omega)$ there exists a relation

$$X(\omega) = A(\omega_1, \omega_2)X(\omega_1)X(\omega_2) \; ; \; \omega = \omega_1 \pm \omega_2 \tag{3}$$

where physically $X(\omega_1)$ and $X(\omega_2)$ represent the amplitudes of the primary interacting waves and $X(\omega)$ denotes the amplitude of the resulting sum or difference frequency wave. The quantity $A(\omega_1, \omega_2)$ is the coupling coefficient. The goodness of the quadratic (i.e., double product) relation in Eq. (3) can be measured by a quadratic correlation coefficient [5],

$$\rho(\omega_1, \omega_2) = \frac{E\left[X(\omega_1)X(\omega_2)X^*(\omega)\right]}{E\left[|X(\omega_1)X(\omega_2)|^2\right]^{\frac{1}{2}} E\left[|X(\omega)|^2\right]^{\frac{1}{2}}} \; ; \; \omega = \omega_1 \pm \omega_2 \; . \tag{4}$$

The quantity $\rho(\omega_1, \omega_2)$ basically measures the degree of quadratic correlation on a spectral basis and is analogous to the coherency spectrum $|\gamma_{12}(\omega)|$ which is a measure of the degree of linear correlation between two signals on a spectral basis [6]. Since the waves at ω_1 and ω_2 are statistically independent of each other, $|\rho(\omega_1, \omega_2)|$ reduces to Eq. (2). With the aid of the Schwarz' inequality one can show that $|\rho(\omega_1, \omega_2)|$, and thus $b(\omega_1, \omega_2)$ is bounded by $0 \leq b \leq 1$. Physically, $b(\omega_1, \omega_2)$ will take on a value close to unity when a nonlinear (strictly speaking, quadratic) interaction has taken place. On the other hand, a value of $b(\omega_1, \omega_2)$ near zero suggests an absence of quadratic nonlinearity and thus suggests that any waves present at ω_1, ω_2 and $\omega_1 \pm \omega_2$ are probably spontaneously excited modes of the system rather than (quadratically) coupled modes. Application to experimental data is discussed in a later section.

4. DETERMINATION OF COUPLING COEFFICIENT

In a linear approximation, one represents a random fluctuation in terms of a linear superposition of independent waves. In a real physical system, however, the spectral components of a fluctuation do not always appear to be statistically independent. Rather, some spectral components often show a high degree of coherence to other spectral components which can be measured by the bicoherence spectrum as discussed above. The high degree of coherence between spectral components suggests the following "generalized Fourier series" expansion of a random fluctuation, i.e.,

$$x(t) = \sum_{\omega} X^{(1)}(\omega) e^{-i\omega t} + \sum_{\omega_1, \omega_2} A(\omega_1, \omega_2) X^{(1)}(\omega_1) X^{(1)}(\omega_2) e^{-i(\omega_1 + \omega_2)t} + \ldots \quad (5)$$

where $A(\omega_1, \omega_2)$ is a quadratic coupling coefficient. After Fourier transforming each side, Eq. (5) becomes

$$X(\omega) = X^{(1)}(\omega) + X^{(2)}(\omega) + \ldots \quad (6)$$

where

$$X^{(2)}(\omega) = \sum_{\omega_1+\omega_2 = \omega} A(\omega_1, \omega_2) X^{(1)}(\omega_1) X^{(1)}(\omega_2) \quad . \tag{7}$$

Clearly, $X^{(1)}(\omega)$'s represent the complex amplitudes of the statistically independent "linear waves" and $X^{(2)}(\omega)$ is the amplitude of the sum and difference frequency waves due to a quadratic nonlinear interaction of $X^{(1)}(\omega)$'s. As a special case, suppose that there exists only one set of ω_1 and ω_2 which satisfies the constraint $\omega = \omega_1 \pm \omega_2$. In other words, only two waves at ω_1 and ω_2 interact and generate a third and a fourth wave at the sum and difference frequencies. Then Eq. (7) can be written as

$$X(\omega) = A(\omega_1, \omega_2) X(\omega_1) X(\omega_2) \tag{8}$$

which is equivalent to Eq. (3). Next we multiply each side of Eq. (8) by $X^*(\omega_1)X^*(\omega_2)$ and take an expectation value to get

$$E\left[X^*(\omega_1)X^*(\omega_2)X(\omega)\right] = A(\omega_1, \omega_2) E\left[|X(\omega_1)|^2 |X(\omega_2)|^2\right] \quad . \tag{9}$$

Making use of the fact that the waves at ω_1 and at ω_2 are statistically independent of each other, we finally obtain the following expression

$$A(\omega_1, \omega_2) \approx \frac{1}{T} \frac{B^*(\omega_1, \omega_2)}{P(\omega_1)P(\omega_2)} \quad . \tag{10}$$

This is a very important result since it basically states that the complex quadratic coupling coefficient $A(\omega_1, \omega_2)$ can be expressed in terms of experimentally available spectral quantities, namely the auto-power spectra $P(\omega_1)$ and $P(\omega_2)$, and the bispectrum $B(\omega_1, \omega_2)$. The physics of the nonlinear interaction is, of course, imbedded in the interaction coefficient.

5. EXAMPLES OF EXPERIMENTAL APPLICATIONS OF BISPECTRAL ANALYSIS

The ideas and concepts expressed in the preceding sections are quite general in that they are applicable to all wave phenomena, e.g.,

electromagnetic, seismic, and acoustic waves. To demonstrate the utility of these techniques we now apply them to wave phenomena observed in plasmas. Acoustic-type waves propagating in plasmas give rise to a space-time modulation of the plasma density. These fluctuations in density are monitored with Langmuir probes, digitized with the aid of Biomation 8100 waveform recorders, and transferred to magnetic tape under the control of an LSI-11 microcomputer. The magnetic tapes are then read at a later time and the data analyzed on a CDC 6600 computer. Although the bispectrum $B(\omega_1, \omega_2)$ is defined over the entire $\omega_1 - \omega_2$ plane, we make use of its symmetry conditions and plot it only in the first quadrant. Furthermore, since the data is digitized, the highest spectral frequency plotted is given by the Nyquist frequency f_N. Consequently, in the figures that follow the bicoherence spectrum is plotted in a triangular region of the first quadrant defined by $0 \le f_1 \le f_N$, $f_1 \le f_2$, $f_1 + f_2 \le f_N$.

Identification of Nonlinearly Coupled Waves

In Fig. 1 is shown a self-excited fluctuation spectrum which was observed during a study of the evolution of drift-wave turbulence [7]. In the middle portion of the figure is shown a three-dimensional plot of the bicoherence spectrum, and at the bottom is shown a contour plot. In particular, we wish to consider the waves oscillating at frequencies $f_a = 28$, $f_b = 53$, $f_c = 81$, $f_d = 134$, and $f_e = 162$ kHz. Each wave was identified as a drift wave propagating mainly in the azimuthal direction. The phase spectrum (not shown) indicates that these waves are not dispersive, and thus the nonlinear wave interaction selection rules for wavenumber will be automatically satisfied, if the frequency selection rules are satisfied.

Note that the bicoherence spectrum in Fig. 1 exhibits several peaks located at (f_a, f_b), (f_b, f_c), and (f_c, f_c). Let us first consider the peak at (f_c, f_c). Since $f_e = 2f_c$, harmonic generation is suggested and in fact the peak at (f_c, f_c) indicates that the wave at f_e is the genuine second harmonic of the wave at f_c. Next, the peaks at (f_a, f_b) and (f_b, f_c) also indicate phase coherence between the waves f_b and f_c, and the difference frequency wave $f_a = f_c - f_b$ and the sum frequency wave $f_d = f_c + f_b$. Thus the bicoherence spectrum indicates that the waves present at f_a, f_b, f_c, f_d, f_e are coupled, rather than independently excited.

In Fig. 2 is shown a turbulent power spectrum and below it the corresponding bicoherence plots. In the turbulent regime we might synthesize the power spectrum in terms of many independent oscillators operating at different frequencies. These oscillators are, of course, characterized by statistically independent phases. Under such conditions we would expect the bicoherence spectrum to be near zero and, indeed, the computer-generated bicoherence plot is very near zero for all combinations of f_1 and f_2.

Experimental Determination of Coupling Coefficients

Equation (10) indicates that the coupling coefficient $A(\omega_1, \omega_2)$ may be obtained from measurements of the bispectrum and the auto-power spectrum. Our work [8] on this phase of the problem is fairly recent and, therefore, the results are somewhat preliminary. To test the feasibility of experimentally determining coupling coefficients we have applied the approach to ion-acoustic wave harmonic generation in plasmas. The power and phase spectra are shown in the upper half of Fig. 3. Harmonics of the fundamental (16 kHz) are clearly evident at 32 and 48 kHz. The respective azimuthal mode numbers are determined from the phase spectrum as m = 1, 2, and 3. Note that the bicoherence spectrum shown in the lower half of Fig. 3 exhibits strong peaks at (f_A, f_A) and $(f_A, 2f_A)$ corresponding to generation of the first and second harmonic.

The harmonic generation coupling coefficient $A(f_A, f_A)$ relating the amplitude of the first harmonic $(2f_A)$ to the fundamental (f_A) was determined in the following way. The fluctuating waveform was digitized and Fourier transformed on the computer using the FFT algorithm. Next, the auto-power spectrum and the bispectrum were computed from the Fourier transforms and the coupling coefficient computed using Eq. (10).

The results are given in Table 1 for three different observations (i.e., observations made under different experimental conditions) of ion acoustic harmonic generation. In Table 1 the symbol V is used to indicate a dimensionless coupling coefficient and thus distinguish it from $A(\omega_1, \omega_2)$ which, as indicated by Eq. (8), has the same dimensions as $1/X(\omega)$. We also note that only the modulus of the coupling coefficient is shown in Table 1. For comparison purposes we have also indicated the theoretical value of the coupling coefficient based on a nonlinear theory which was carried out under a research grant from the Texas Atomic Energy Research

Foundation. The good agreement between theory and experiment gives us confidence that indeed coupling coefficients characterizing quadratic nonlinear interactions may be determined from experimental measurements of the bispectrum.

6. SUMMARY

On the basis of the examples cited in the preceding section, it does appear practical to utilize digitally implemented bispectral analysis as an aid in analyzing and interpreting fluctuation data characterized by nonlinear or parametric wave interactions. It should also be stressed that such concepts and techniques apply to all wave phenomena. For example, such techniques may possibly be useful in analyzing parametric-radar data corresponding to scattering from a rough sea. Bispectral analysis may also provide additional signature information by which various radar targets may be classified.

This work on bispectral analysis of nonlinear wave interactions will be described in greater detail in journal articles that will be prepared and written within the next few months.

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Table 1. Experimental and Theoretical Determination of Harmonic Generation Coupling Coefficients.

Example	$\|V\|_{BISPECTRUM}$	$\|V\|_{THEORY}$
No. 1	0.48	0.46
No. 2	0.45	0.45
No. 3	0.58	0.45

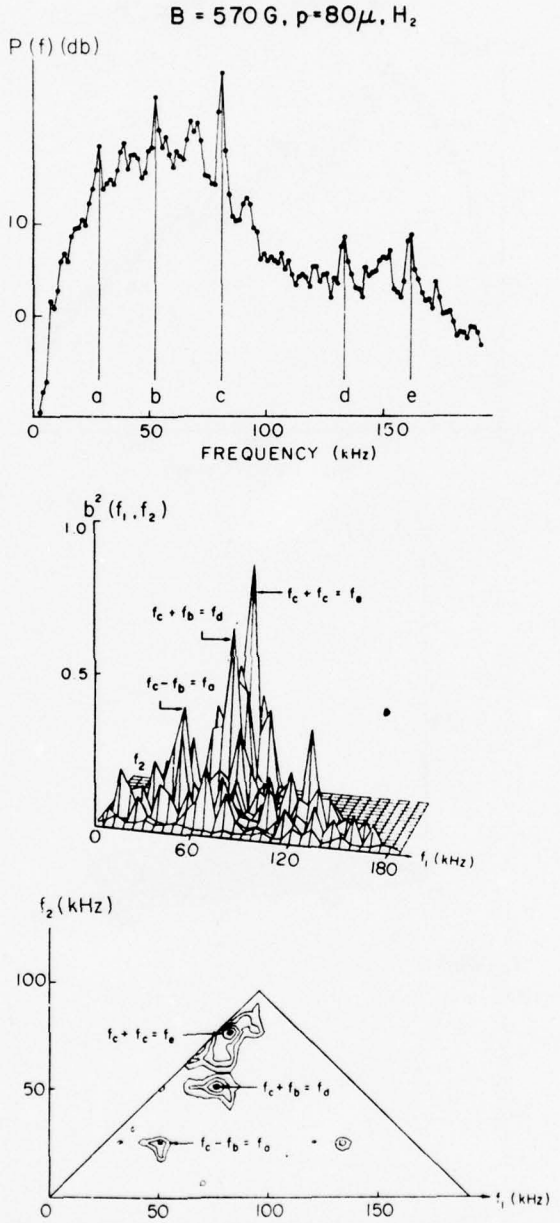

Figure 1. Computer Generated Plots of an Auto-Power Spectrum (top) and the Corresponding Bicoherence Spectrum (middle) for a Case of Wave-Wave Interaction. Shown at the Bottom Is a Contour Plot of the Bicoherence Spectrum.

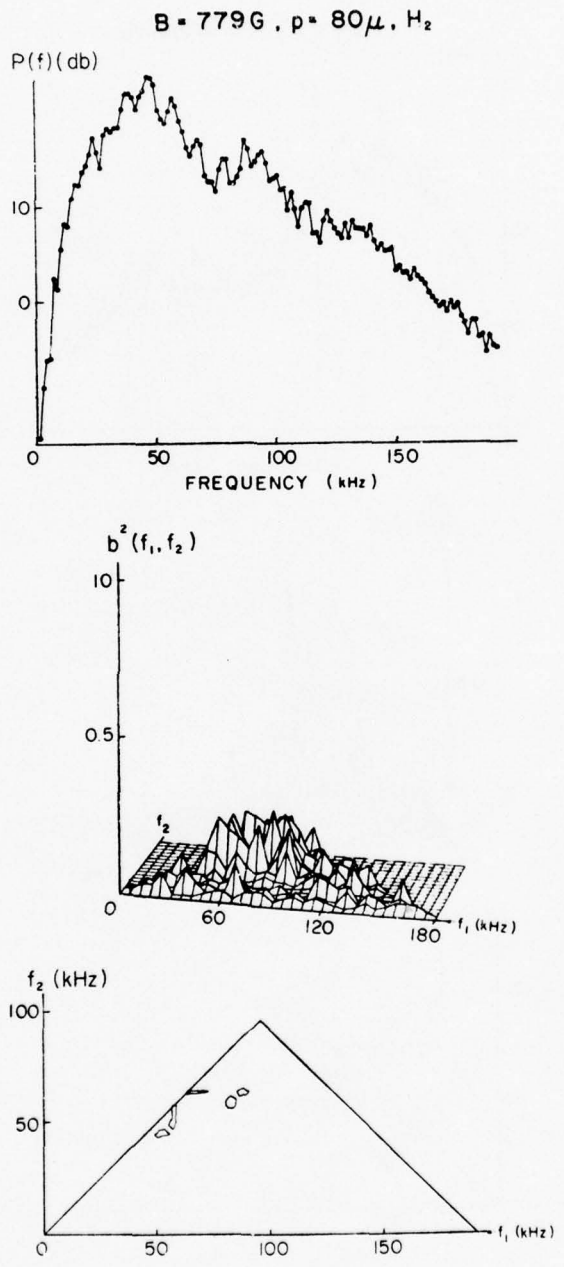

Figure 2. Computer Generated Plot of an Auto-Power Spectrum (top) and the Corresponding Bicoherence Spectrum (middle) for the Case of a Turbulent Power Spectrum. Shown at the Bottom Is a Contour Plot of the Bicoherence Spectrum.

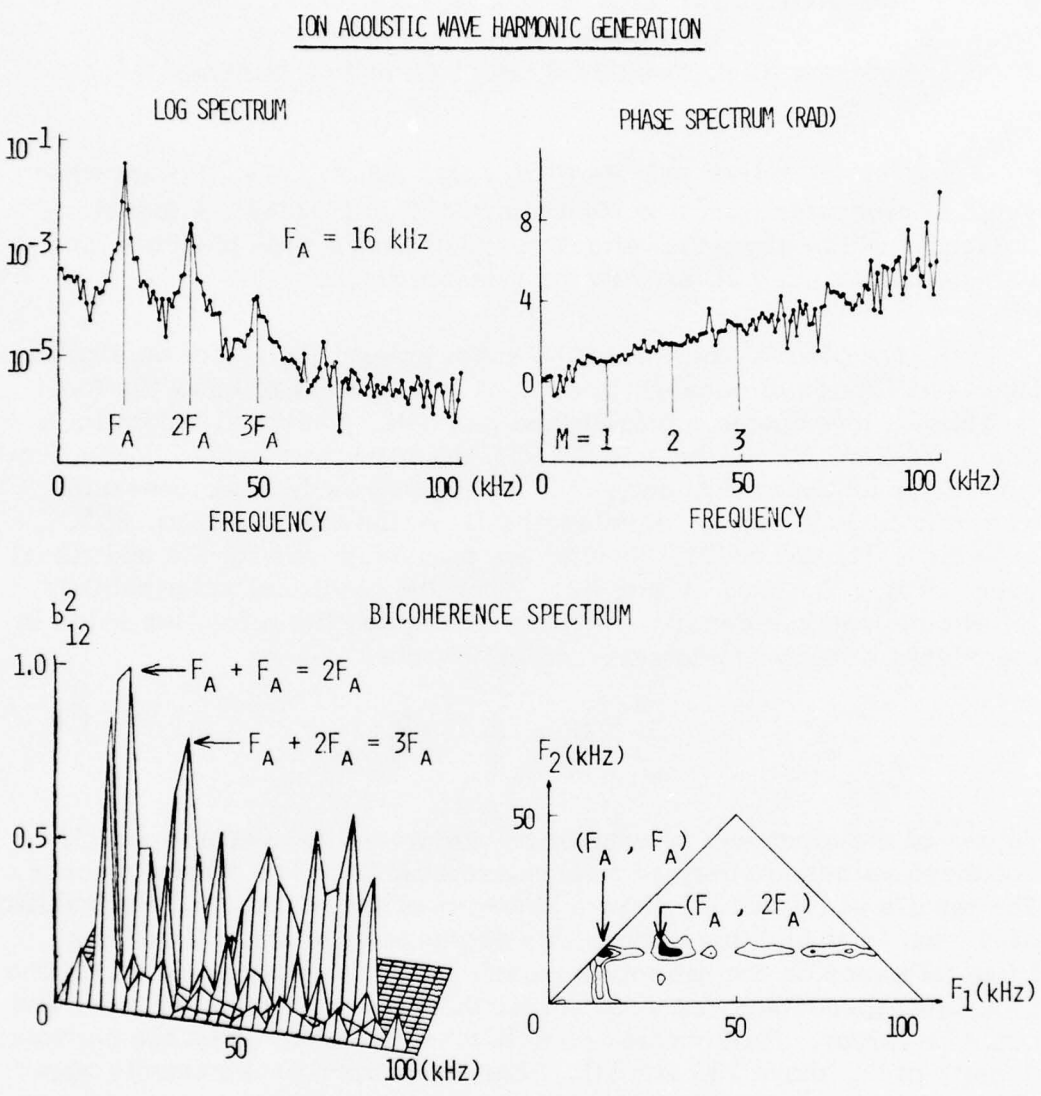

Figure 3. An Example of Ion-Acoustic Harmonic Generation. Shown in Top Left Is the Cross-Amplitude Spectrum and on the Right the Corresponding Phase Spectrum. At the Bottom Left Is the Corresponding Bispectrum and to the Right Is Shown the Corresponding Contour Plot.

B. REFRACTIVE INDICES OF H_2, D_2, He, O_2 AND Ne UP TO 2000 ATMOSPHERES†

Professor A. A. Dougal, S. H. Baek and G. Schürger*

The refractive indices of H_2, D_2, He, O_2 and Ne were measured at pressures from 1 to 2060 atm, 25°C and 6328Å. A formula is presented which gives the refractive index over a wide pressure range using coefficients derived from the measurements.

For optical experiments in super pressure gases or applications like laser-fusion of gaseous targets, it is important to know the focal length of a lens inside a pressurized gas cell. The focal length for a given pressure (P) can be calculated if the refractive index (n) as a function of the pressure is known. Earlier workers made direct measurements up to 2000 atm for wavelengths (λ) in the visible range, 25°C, only for N_2 [1] and Ar [2]. Results are presented here for the additional gases of H_2, D_2, He, O_2 and Ne. When the electrical polarizability (α) and the particle density (N/V) are available, the refractive index is calculated through the Lorentz-Lorenz formula

$$\frac{n^2 - 1}{n^2 + 2} = \frac{4}{3} \pi \alpha \frac{N}{V} \quad . \tag{1}$$

Values of the electrical polarizability are given, for example, in [3]. Yet these values are derived from measurements in low pressure gases. The results of [1] and [2] show a decrease of the electrical polarizability of N_2 and Ar at high pressure. This decrease is around 1% and has little influence on the refractive index calculation through Eq. (1). The pressure dependence was unknown for the gases investigated here, and could be larger. Furthermore, no data was published about the particle density of O_2 above 135 atm [4]. Therefore direct measurements were necessary to get reliable values of the refractive indices of the investigated gases in the super pressure range.

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The experimental technique utilized an interferometer located inside a super pressure cell with illumination from a He-Ne laser at 6328Å as is shown in Fig. 1. Two glass discs were mounted in a holder. Three screws permitted alignment of the discs relative to each other. The reflections of the laser beam on the inner surfaces of the discs produced a circular interference pattern at the photomultiplier tube. In order that the reflections from the outer surfaces of the discs and from the cell window did not disturb the desired interference pattern, each disc had a slanted outside surface. The two inner surfaces were tilted off the perpendicular to the cell window.

For each run the cell was fully pressurized, and subsequently gas slowly was released. A small aperture over the photomultiplier was aligned to the center of the interference pattern. As the pressure decreased, the output of the photomultiplier undulated and was recorded. An m-fold undulation is correlated with a refractive index change Δn through $\Delta n \cdot 2d = m\lambda$, the change in the optical pathlength (d is the distance between the glass discs). We ignore that the reflecting surfaces were slightly less than perpendicular to the laser beam axis. The purity of the gases, as stated by the manufacturers, was 99.999% for H_2, He, and Ar; 99.995% for Ne; 99.99% for N_2; 99.95% for O_2 and 99.5% for D_2.

From the m-fold undulations, values of the refractive index of the different gases are calculated and presented in Table 1, and graphically displayed in Fig. 2. The gas pressure was recorded using a bourdon gauge. We checked and recalibrated the gauge by measuring the refractive indices of N_2 and Ar and then comparing it with the earlier data of Michels and coworkers [1,2]. Our measured values for N_2 and Ar are also included in Fig. 2. The maximal error of the pressure reading was ± 6 atm. An additional uncertainty in the calibrating process gives a total possible error of ± 12 atm. The error in n along the ordinate in Fig. 2 is less than 0.05%. The change in the disc separation d due to the hydrostatic compression of the disc holder was calculated from the linearized form of the equation for volume elasticity $\Delta d = d\Delta P/(3 \cdot B)$ where B is the bulk modulus. An elastic compression over the whole pressure range was assumed.

The particle density can be calculated from the virial equation

$$PV_m = kN_AT(1 + BP + \ldots) \qquad (2)$$

where V_m, k, N_A, T and B are the molar volume, the Boltzmann constant, Avogadro's number, the absolute temperature, and the first virial coefficient, respectively. Eqs. (1) and (2) combined, give

$$(A^* + B^*P + \ldots) = \frac{4\pi P}{3kT} \cdot \frac{n^2+2}{n^2-1} \qquad (3)$$

with $A^* = 1/\alpha$ and $B^* = B/\alpha$.

Using the measured values of n for various P in the right side of Eq. (3), we computed by the method of least squares the coefficients of the polynomial in P on the left side. A "best fit" is obtained for all gases for a polynomial $A^* + B^*P$. The computed coefficients A^* and B^* are listed in Table 2. Our results for N_2 and Ar are also included in the table.

From Eq. (3), n can be expressed as

$$n = \left[\frac{C(A^*/P+B^*) + 2}{C(A^*/P+B^*) - 1}\right]^{\frac{1}{2}} \text{ with } C = 9.6976 \times 10^{-21} \text{cm}^3 \cdot \text{atm} . \qquad (4)$$

Now Eq. (4) permits calculation of the refractive index ($n_{cal.}$) at 6328Å and 25°C over the full pressure range. The difference between $n_{cal.}$ and n from Table 1 is shown in the lower portion of Table 2. Also shown is the difference between $n_{cal.}$ and $n_{lit.}$, where $n_{lit.}$ are the values taken from the literature. They are either directly measured or calculated by the Lorentz-Lorenz formula from the measured isotherms together with appropriate values of the electrical polarizability

$$(\alpha_{H_2} = 0.790 \times 10^{-24} \text{cm}^3, \quad \alpha_{D_2} = 0.775 \times 10^{-24} \text{cm}^3 ,$$

$$\alpha_{He} = 0.21 \times 10^{-24} \text{cm}^3 , \quad \alpha_{He} = 0.39 \times 10^{-24} \text{cm}^3) \quad [9,3] .$$

The relatively good agreement for these gases shows that the change of α with the pressure is low. Using our measurements of n and the particle densities from [7] and [8] we calculated α for He and Ne by Eq. (1). The results gave a decrease of α of the same order as was reported previously for N_2 and Ar.

The absence of higher order terms in the polynomial used in Eq. (4) and the results for $n_{cal.} - n_{lit.}$ in Table 2 give us confidence that Eq. (4) can be used for still higher pressures than 2000 atm.

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* During the period of this research, G. Schürger of the Ruhruniversität, Bochum, West Germany, was the recipient of a Research Fellowship from the North Atlantic Treaty Organization, and was an Exchange Visitor to the United States.

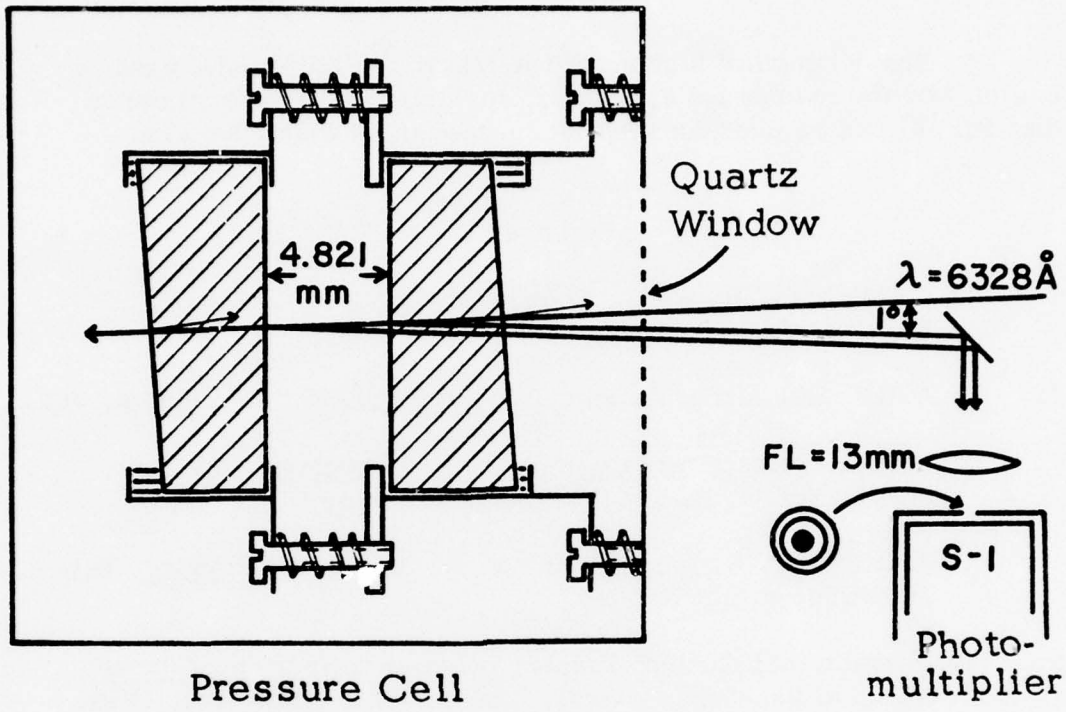

Figure 1. Diagram of Experimental Arrangement for Refractive Index Measurements of Compressed Gases Up to 2060 atm.

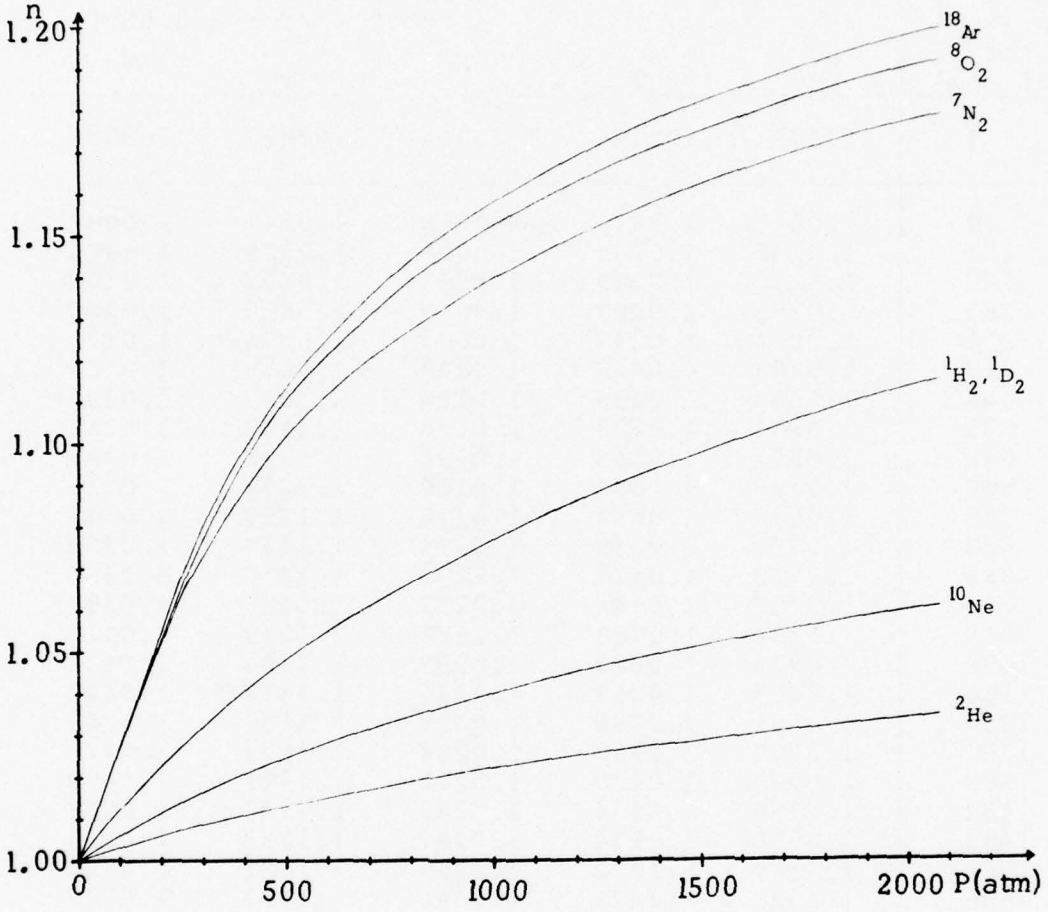

Figure 2. Pressure Dependence of the Refractive Index for Different Gases at 25°C.

Table 1. Refractive Index n at 6328Å and 25°C.

p (atm) (error ± 12 atm)	n (error < 0.05%)				
	H_2	D_2	He	O_2	Ne
1 ‡	1.00014	1.00014	1.00004	1.00027	1.00007
50	1.0070	1.0070	1.0018	1.0142	1.0037
124	1.0145	1.0145	1.0038	1.0325	1.0076
185	1.0210	1.0209	1.0056	1.0491	1.0108
263	1.0293	1.0289	1.0078	1.0693	1.0148
331	1.0351	1.0347	1.0093	1.0834	1.0179
397	1.0405	1.0403	1.0109	1.0953	1.0208
466	1.0458	1.0456	1.0124	1.1057	1.0236
535	1.0506	1.0503	1.0138	1.1143	1.0261
602	1.0551	1.0548	1.0151	1.1216	1.0285
684	1.0605	1.0600	1.0166	1.1296	1.0312
756	1.0647	1.0642	1.0179	1.1357	1.0335
823	1.0683	1.0679	1.0191	1.1409	1.0355
888	1.0718	1.0714	1.0201	1.1456	1.0374
951	1.0752	1.0748	1.0212	1.1496	1.0392
1018	1.0784	1.0780	1.0222	1.1539	1.0410
1098	1.0823	1.0819	1.0235	1.1582	1.0431
1166	1.0853	1.0849	1.0245	1.1617	1.0447
1236	1.0881	1.0878	1.0255	1.1649	1.0463
1301	1.0906	1.0905	1.0264	1.1678	1.0477
1363	1.0929	1.0928	1.0272	1.1702	1.0490
1432	1.0956	1.0954	1.0280	1.1730	1.0503
1492	1.0978	1.0974	1.0287	1.1753	1.0515
1567	1.1004	1.1002	1.0296	1.1781	1.0529
1636	1.1027	1.1024	1.0304	1.1803	1.0542
1699	1.1047	1.1045	1.0312	1.1825	1.0553
1763	1.1068	1.1065	1.0319	1.1845	1.0564
1827	1.1088	1.1085	1.0326	1.1863	1.0574
1887	1.1106	1.1103	1.0332	1.1881	1.0583
1945	1.1123	1.1118	1.0338	1.1896	1.0592
2007	1.1142	1.1137	1.0344	1.1913	1.0602
2060	1.1158	1.1153	1.0350	1.1927	1.0611

‡ Data from [5]

Table 2. Coefficients A* and B* of Eqs. (3) and (4) and Comparison of the Calculated Refractive Indices Using Eq. (4) With the Measured Values and the Values Taken From the Literature.

	H_2	D_2	He	N_2	O_2	Ne	Ar
$A^* \times 10^{-24}$ cm^3	1.197	1.205	4.703	0.471	0.457	2.363	0.446
$B^* \times 10^{-20}$ $cm^3 \cdot atm$	8.042	8.048	22.449	6.665	6.049	14.434	5.786
$\lvert n_{cal.} - n \rvert$	$<2 \cdot 10^{-3}$	$<2 \cdot 10^{-3}$	$<7 \cdot 10^{-4}$	$<4 \cdot 10^{-3}$	$<7 \cdot 10^{-3}$	$<8 \cdot 10^{-4}$	$<7 \cdot 10^{-3}$
$\lvert n_{cal.} - n_{lit.} \rvert$	$<4 \cdot 10^{-3}$ (up to 2946atm)	$<4 \cdot 10^{-3}$ (up to 2755atm)	$<2 \cdot 10^{-3}$ (up to 1000atm)	$<3 \cdot 10^{-3}$ (up to 2053atm)		$<2 \cdot 10^{-3}$ (up to 2824atm)	$<6 \cdot 10^{-3}$ (up to 2370atm)
	[6]	[6]	[7]	[1]		[8]	[2]

C. A GENERALIZED MODEL FOR NONCOHERENT OPTICAL CONVOLVERS AND CORRELATORS†

Professor Jerome Knopp

In previous research discussing optical convolution or correlation in noncoherent light, three basic types of devices‡ have been described for performing these operations. (See Fig. 1.) [1,2,3,4,5,6] In each of these devices, the two dimensional intensity transmittance of two transparencies is convolved or correlated. In the discussion that follows, reference will be made only to convolution with the tacit understanding that the same ideas apply to correlation. (A device which convolves becomes a correlator by simply inverting and reversing one of the transparencies.) The specific operation of the convolvers shown has been explained in the literature cited and they will not be discussed further except in a more general context to be explained below.

In past research experiments using a convolver of the "misfocus" type shown in Fig. 1(b), it was found that moving transparency τ_2 away from the lens still resulted in a convolution. A geometric analysis of this situation showed that the impulse response due to an impulse at τ_1 results in a scaled spatially invariant image of τ_2 ‡ no matter what the distance between τ_2 and the lens. This distance effects only the scaling of the impulse. There is no reason to mount τ_2 as close as possible to the lens (unless some peculiar scaling between τ_1 and τ_2 is needed). This result is interesting, and applying it conceptually leads to the generalized version of a single lens convolver shown in Fig. 2. The resulting optical convolution between τ_1 and τ_2 is described by

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†This research was supported in part by the Joint Services Electronics Program under Contract F44620-76-C-0089 and in part by the M.I.T. Lincoln Labs, where Dr. Knopp is presently on the staff.

‡ This discussion does not include devices which use mechanical shifters to shift one transparency with respect to the other.

‡ This analysis holds, assuming the usual small angle assumptions made in analyzing optical convolvers.

$$I(x',y') = K \int_{-\infty}^{+\infty}\int \tau_1\left(\frac{x}{m_1}, \frac{y}{m_1}\right) \tau_2 \left(\frac{x'-x}{m_2}, \frac{y'-y}{m_2}\right) \frac{dx}{m_1} \frac{dy}{m_1}, \quad (1)$$

where K is a constant that accounts for the transilluminance of the incoherent source. The constants m_1 and m_2 are the magnification factors of τ_1 and τ_2 respectively. These factors can be found by replacing one transparency with a δ-function (mathematical impulse or physically a pinhole) and observing the image size of the other transparency in the plane of convolution. These magnification factors can also be found in terms of the object-image geometry given in Fig. 2. It can be shown that

$$m_1 = \frac{i_2}{i_2 - o_1} \cdot \frac{C}{o_2}, \quad (2)$$

and

$$m_2 = \frac{i_1 - C - o_2}{i_1}. \quad (3)$$

By appropriately adjusting the distances shown in Fig. 2 and the focal length of the lens, it is possible to consider any one of the basic three types of convolvers as a special case of the generalized convolver shown in Fig. 2. This conceptually relates the convolvers shown in Fig. 1 and in practice results in a more flexible system. Furthermore, it should be pointed out that Eq. (1) can be extended to any multi-lens system where a convolution will always occur at planes of misfocus.

The preceding analysis did not account for the finite size of the system elements. This results in vignetting and bandwidth limitations due to diffraction effects. These effects are discussed in the recent literature [7].

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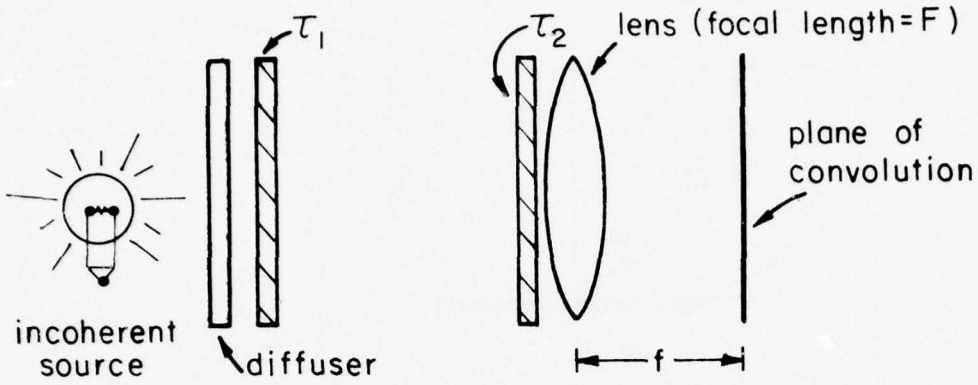
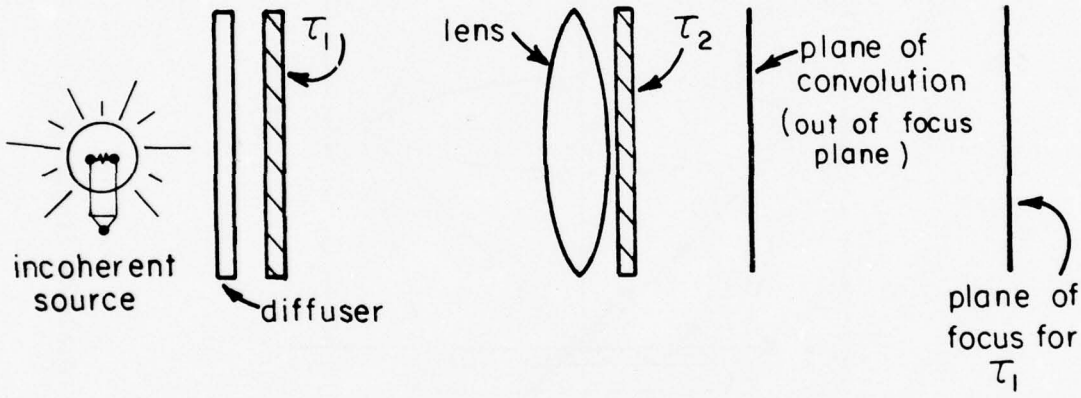
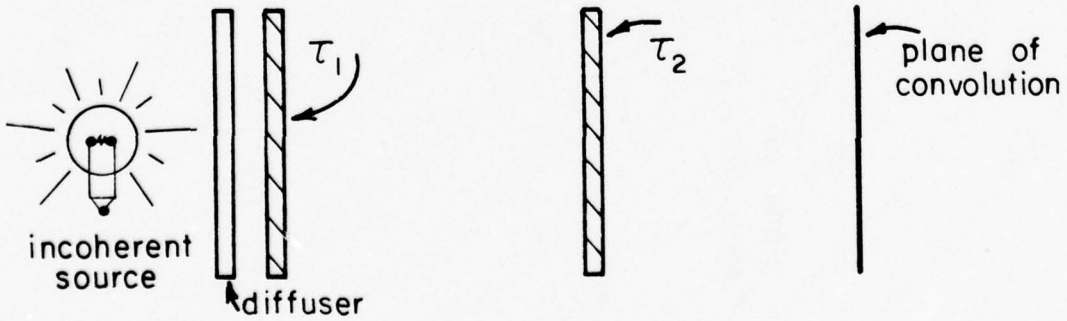


(Figure 1a. Convolution Using Angular Projection.)



(Figure 1b. Convolution Using a Plane of Misfocus.)



(Figure 1c. Convolution Using Shadow Projection.)

Figure 1. Three Basic Types of Optical Convolvers.

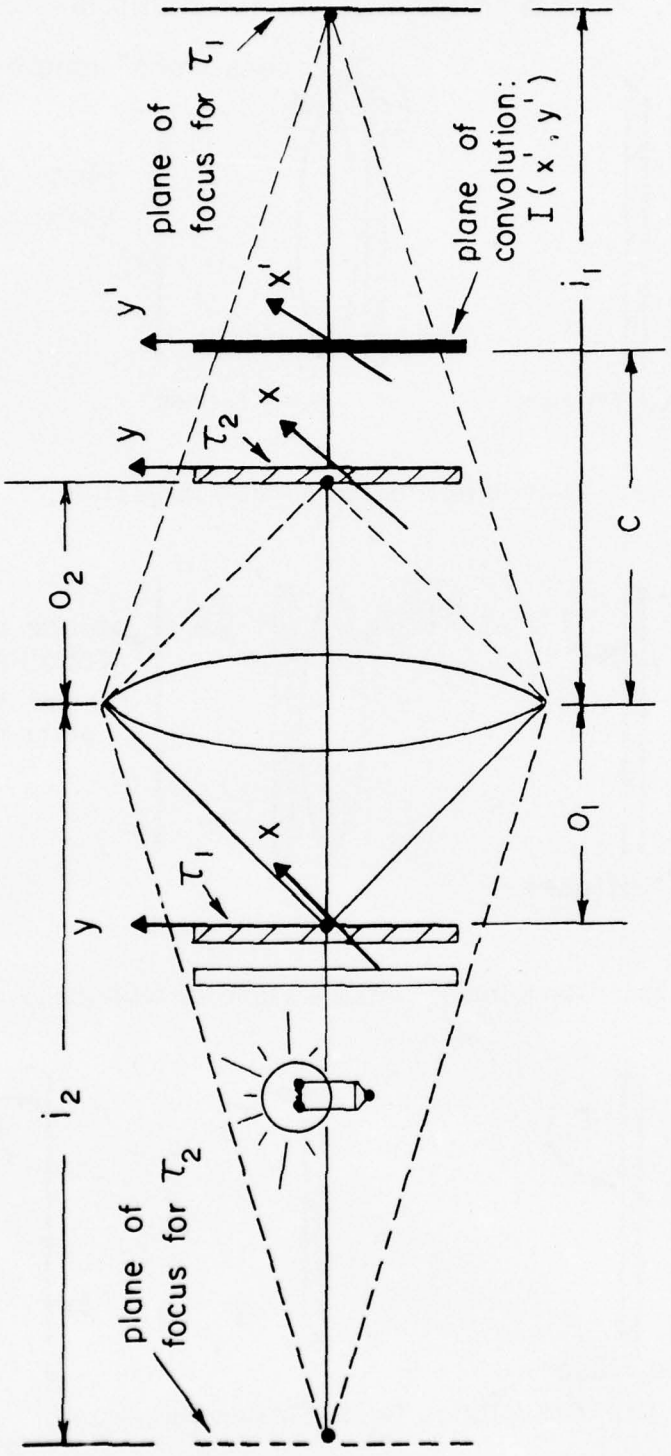


Figure 2. Generalized Single Lens Convolver/Correlator.

D. INFRARED NONLINEAR OPTICS IN MOLECULAR GASES†

Professor Michael F. Becker, Min Ho Kang, and Kang Min Chung

We have demonstrated optimized third harmonic generation in SF_6 at 10.6 microns. Phase matching and optimum focusing were studied. Measurements of the third harmonic susceptibility show that there is significant population redistribution within the vibrational energy ladder. The susceptibility was saturated at higher laser intensities due to power broadening and AC Stark shifting of the resonant energy levels. These effects limit the third harmonic conversion efficiency to less than 10^{-8} for 40 ns CO_2 TEA laser pulses.

Optical third harmonic generation (THG) has been successful [1,2,3] in the visible and ultraviolet. THG in molecular gases at infrared wavelengths had not been demonstrated [4,5,6] until late 1975. This delay is due to the smaller vibrational-rotational transition matrix elements (as compared to the electronic matrix elements) and the longer wavelength itself. However, the choice [7] of a molecular gas such as SF_6 can alleviate the first obstacle by utilizing a triple resonance enhancement in the TH susceptibility at CO_2 TEA laser frequencies. We generated a maximum TH power of 10 mW with an input of 2 MW on the P(24) line of the 10.6 micron band. Two significant factors are identified which limit the potential conversion of triple resonance enhanced THG. First, absorption at the fundamental frequency reduces the effectiveness of phase matching to an enhancement of only five times the non-phase matched conversion and prevents any improvement by further increases in the SF_6 pressure. Second, saturation of the TH susceptibility causes the observed TH power to fall below the expected cubic dependence on incident laser power.

Absorption measurements on SF_6 at the P(20) line of the 10.6 micron band have been reported for power densities lower than 2 MW/cm^2 by Armstrong and Gaddy.[8] We extended these measurements to the range of 40 MW/cm^2 to 300 MW/cm^2, representative of our third harmonic generation experiments. The saturated absorption coefficient at 200 MW/cm^2 is 1/100 of the unsaturated value of .45cm^{-1} $torr^{-1}$ and agrees

†This research was supported in approximately equal parts by the Joint Services Electronics Program under Contract F44620-76-C-0089; the National Science Foundation; and the Texas Atomic Energy Research Foundation.

with the theory. [8,9] This residual absorption has a deleterious effect on the TH conversion. Figure 1 shows the calculated behavior of TH power as a function of pressure for SF_6 and for an ideal lossless gas similar to SF_6 in all other aspects. The points represent the experimental data for SF_6. It is evident that the ultimate conversion in a lossy medium is severely limited regardless of phase matching conditions.

Figure 2 shows the calculated TH susceptibility versus frequency. Again, the points represent experimental data. Effects of saturation of the susceptibility have been removed by extrapolating the cubic slope of the TH power versus input power data. While both experiment and theory show sharp resonance effects, the experimental data falls below the theoretical curves. This is due to the severe population redistribution within the vibrational quantum system. Our theory assumes that the molecules remain in their room temperature energy distribution and that only vibrational ground state molecules contribute to the susceptibility, although this will not be true for power densities over 40 MW/cm^2. The strongly saturated absorption is clear evidence of a population redistribution. In fact, at the absorption line center (947.9 cm^{-1}, near the P(16) laser line), the deviation of the experimental susceptibility is strongest. Consider, however, the effective susceptibility of a molecule in the $\upsilon_3 = 3$ vibrational level. The susceptibility for this molecule is about 10^{-47} M^3/V^2 in good agreement with the experiment. A more accurate comparison, however, is very difficult since we must know the exact population distribution within the complex vibrational energy ladder as a function of time and laser intensity. This remains as future work.

Evidence of saturation of the nonlinear susceptibility through power broadening [10] and AC stark shift is seen in plots of TH intensity versus fundamental intensity. Representative curves for several different laser frequencies are shown in Fig. 3. The P(24) line gives the greatest ultimate TH signal with P(22), P(26), and P(20) being next highest, in that order. If one resonant transition is significantly power broadened, the slope is reduced from 3 to 2, and likewise to 1 if two levels become broadened, and to 0 if all three levels are broadened. Figure 3 suggests that a single level is power broadened for the P(22) line, and that two levels are power broadened for the P(20) line at about the same laser intensity. No power broadening is observed for the P(24) line. Quantitative analysis of the power broadening is in progress and preliminary results look reasonable if AC stark shifts are included. It appears

that before all three levels become broadened, catastrophic disruption of the SF_6 occurs. This is accompanied by broadband visible and infrared emission. At 1.8 torr, the absolute molecular dissociation probability [11] is 0.2%. At this energy density (8 j/cm^2) a majority of the molecules will reside in the continuum of upper energy levels. [12] This will further decrease the TH susceptibility and the generated TH power.

In conclusion, we found that the TH conversion efficiency for SF_6 is limited to less than 10^{-8} by the effects of residual saturated absorption, saturation of the TH susceptibility, and by photo-dissociation and breakdown. The second of these effects is not expected to be strongly energy dependent while the last two are energy dependent. Therefore, shorter pulses may generate higher TH powers at least for the P(24) line.

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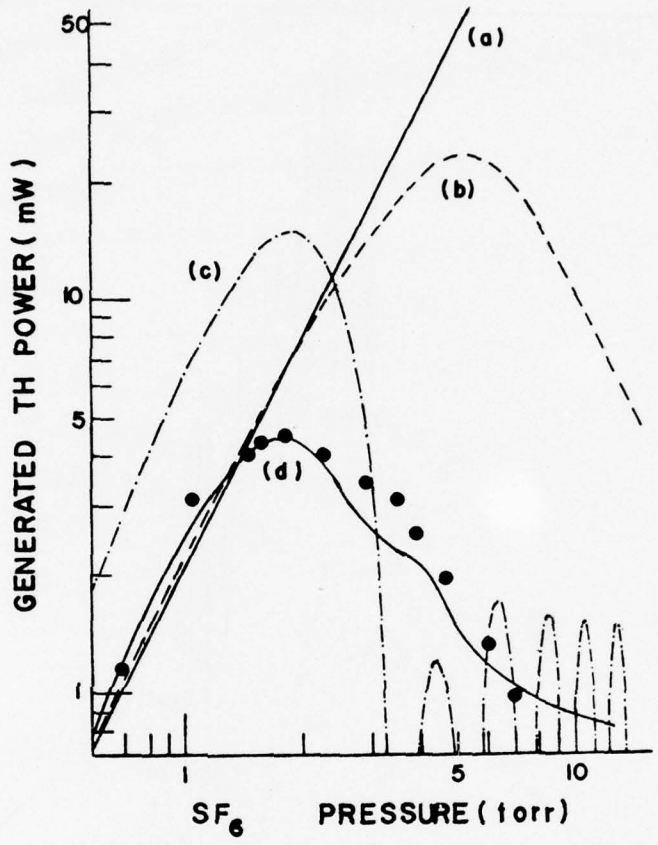

Figure 1. Pressure Dependence of the Third Harmonic Power With Different Phase Matching Conditions.

(a) Perfect phase matching for a lossless medium ($\Delta k = 0$, $\alpha = 0$).

(b) SF_6 at optimum phase matching ($\Delta k = 0.2\Delta k_{SF_6}$, $\alpha = \alpha_{SF_6}$).

(c) A non-phase matched lossless medium ($\Delta k = \Delta k_{SF_6}$, $\alpha = 0$).

(d) Non-phase matched SF_6. Points are experimental data. ($\Delta k = \Delta k_{SF_6}$, $\alpha = \alpha_{SF_6}$).

In all cases L = 23.6 cm, b_0 = 26.4 cm. In (a) - (c), the focus is at the center of cell. In (d), the focus is L/8 from the front of the cell. The laser energy was 0.3 joule, t_p = 40 nsec, on the P(20) line.

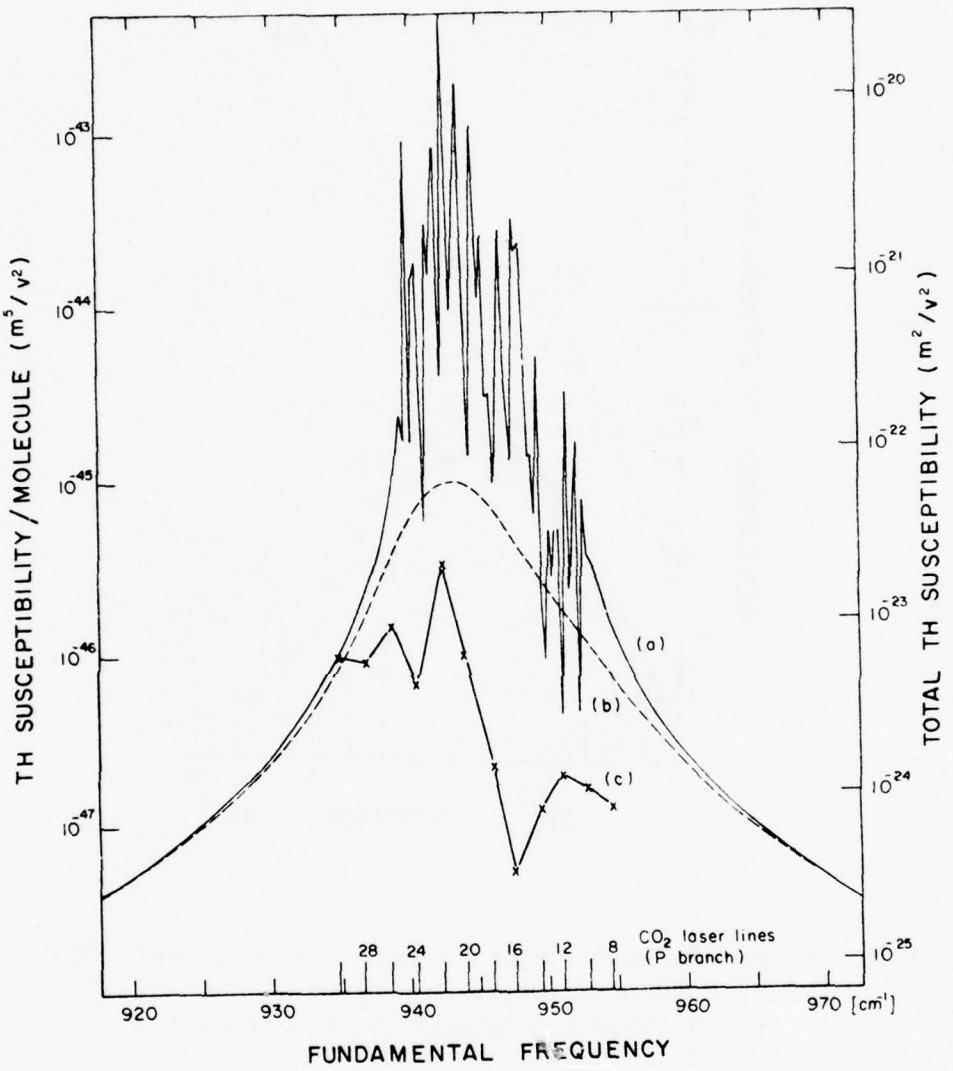

Figure 2. Frequency Dependence of Third Harmonic Susceptibility in SF_6 . Total TH Susceptibility is for a Pressure of 1.78 torr.

(a) Theoretical susceptibility [6] with a linewidth of .001 cm^{-1}, (Doppler linewidth). It is assumed that only the molecules in the ground vibrational state contribute to the susceptibility.

(b) Same as (a) but with a Gaussian linewidth of 10.4 cm^{-1} (corresponding to the entire vibrational absorption band).

(c) Measured susceptibility for P(30) - P(8) CO_2 laser lines.

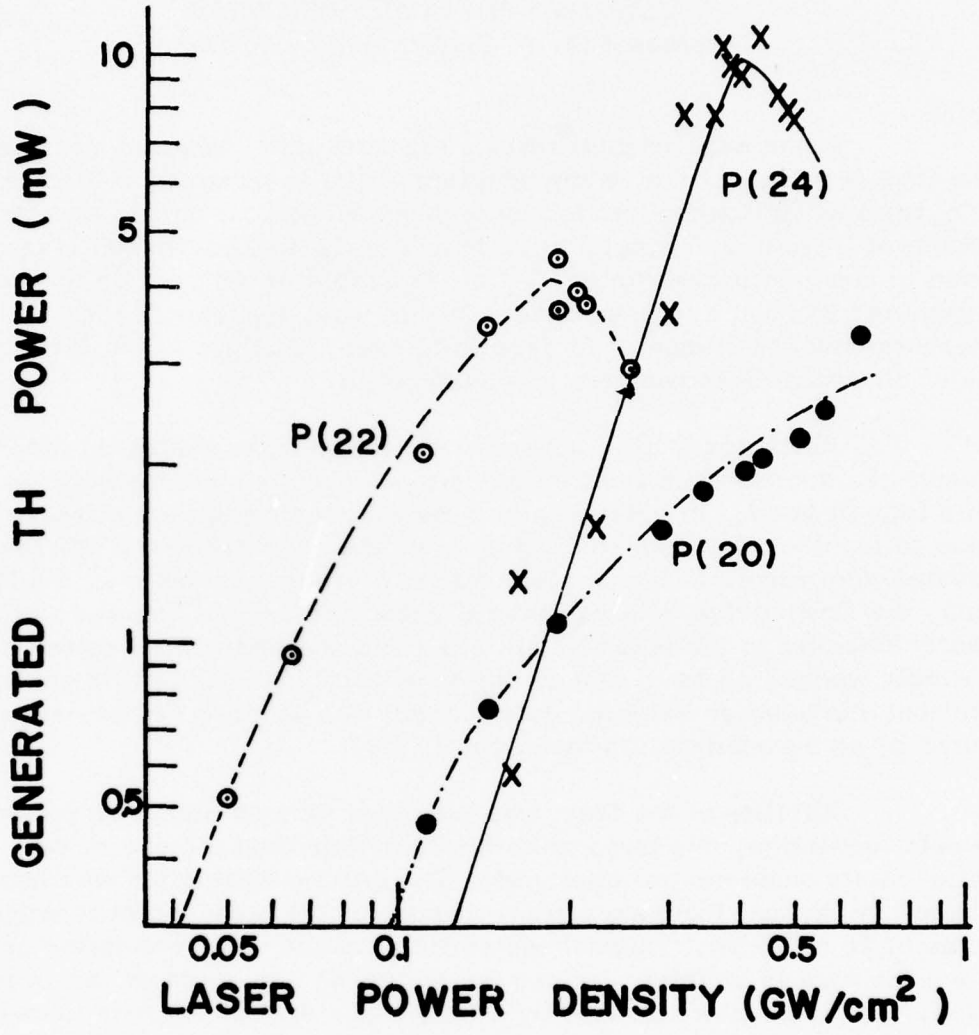

Figure 3. Laser Power Density Dependent Third Harmonic Generation in SF_6 for Various CO_2 Laser Lines in the 10.6 Micron Band. Configuration is the Same as in Fig. 1. The Cubic Dependence of the Third Harmonic Was Measured to Continue Down to 5 μw; This Data Is Not Shown Here.

E. PICOSECOND OPTICAL MEASUREMENTS OF ULTRAFAST PHYSICAL PHENOMENA †

Professor M. F. Becker and R. W. Gunn

In the experimental results reported here, we have measured the time response of the semiconducting-metallic phase transition in VO_2 films at 68°C when excited by picosecond optical pulses at a wavelength of 1 micron. A single pulse from a mode-locked Nd:YAG laser is used in combination with a delay line apparatus to both excite the transition and probe it at a later time. In this way, its response may be measured over the range of 10 psec to 10 nsec. Details of the laser and delay line have been reported previously [1,2].

Final modifications were made to the laser system in order to secure the shortest and most stable mode-locked pulses possible from this type of laser. In order to eliminate all possible etalon effects which tend to lengthen the mode-locked pulses, the ends of the Nd:YAG laser crystal were repolished at angles of 3° to a prism-like shape. In addition, the flowing dye cell was rebuilt such that the dye region was directly adjacent to the laser output mirror and the associated optics were suitably wedged so as to reduce etalon effects further. In this configuration, the average selected pulse length was 35 psec FWHM, as measured by an autocorrelation technique [1,2].

Stability of the laser was improved through precision power supply regulation, dye pump vibration isolation, and the use of two intra-cavity mode contral apertures. The latter modification was necessitated by thermal focusing effects in the Nd:YAG laser rod at repetition rates of 20 to 50 Hz. Thermal instabilities cause beam wandering unless the mode axis is uniquely defined by two irises separated as far as practical. The laser now operates with better than 98% of the pulses well mode-locked. This is close to the statistical limit for passively mode-locked systems.

Preliminary measurements were made on a 2500Å polycrystalline VO_2 film deposited on a sapphire substrate. The film showed a typical change in resistivity of two orders of magnitude at the transition.

† This research was supported entirely by the Joint Services Electronics Program under Contract F44620-76-C-0089.

The sample was mounted in the delay line at the intersection of the initiating and probing beams. The transmission of the films was monitored at 1.06 μ; the reflectivity showed a much smaller change at this wavelength. High quality areas of the sample showed a 78% decrease in transmission as it was passed through the transition temperature by thermal excitation. In the laser initiated dynamic measurements, the substrate temperature was held at 20°C or 53°C; in either case the results were identical since the film heat capacity is negligible, compared to the latent heat of the transition. For laser energy deposition densities below the latent heat of the transition, no change in transmission or reflection was observed. For energy densities higher than the latent heat, the transmission was observed to decrease sharply. However, the transmission decreased by 11%, or only 15% of the change for a thermally excited transition. Also, the decrease occurred in less than 10 psec,[3] the resolution time of this measurement technique.

At energy densities below the latent heat of the transition, no photoexcited carrier absorption was observed. It was expected that the photoexcited carrier lifetime could be measured. Either the carrier lifetime is so short that a significant population never exists, or the band structure is such that no significant change in the transmission occurs regardless of the excited carrier population. This matter will be studied further in order to estimate the photoexcited carrier lifetime. Specific conclusions about the mechanisms driving the phase transition cannot be drawn until the fate of the photoexcited electrons is known.

The incompleteness of the change in transmission has been observed for transitions initiated with 25 to 500 nsec, 1 micron pulses also [4]. This incompleteness may be interpreted as an inhomogeneity in the volume which has changed phase, or as the first, or fast, part of a two step transition. This point also will be investigated further. New films will be used in which the substrate film interaction has been well characterized [5].

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(V. PLASMA AND QUANTUM ELECTRONICS)

F. CHEMICAL KINETICS OF RARE GAS-OXIDE LASERS†

Professor John W. Keto and Charles F. Hart

1. INTRODUCTION

The auroral transition in atomic oxygen $\left(O(^1S_0) \rightarrow O(^1D_2)\right)$ at 5577Å has been of long-standing interest to physicists and chemists. However, recent attention has been focused on the attractive possibility of its use in a high efficiency, high energy laser amplifier [1]. This transition satisfies many of the criteria desirable for such an amplifier:

(1) The lower level $^1D_2$ is more rapidly quenched than is $^1S_0$ by a large variety of gases.

(2) The transition is stable against superfluorescence.

(3) $^1S_0$ has a relatively long lifetime.

(4) Conventional optics may be easily employed with the 5577Å visible wavelength.

In the last few years, a variety of rare gas-oxide mixtures have been shown to lase [2,3], yet adequate kinetic models of the specific reaction sequences necessary for a detailed understanding and operation of these systems is lacking. Insufficient information exists about the mechanisms of excitation transfer from the rare gases to $O(^1S_0)$, and accurate values for many rate constants are required.

This report describes spectral surveys of N_2O in Ar, O_2 in Ar, and O_2 in Ne, which have been taken in our laboratory as the preliminary step in a thorough kinetic study which will be started shortly. These results have indicated those processes where an in-depth study is needed, and have pointed to improvements in the experiment, which are now being instituted.

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†This research was supported entirely by the Joint Services Electronics Program under Contract F44620-76-C-0089.

2. APPARATUS

We are constructing a sophisticated apparatus for kinetic studies on electron-beam excited gas samples. The computer-controlled diagnostic system will monitor both time dependent fluorescence and pulsed dye laser absorption. Over the past year, the hardware for the photon counting and timing system has been completed. Final programming and testing of these systems for kinetic studies is near completion.

Most previous measurements of excitation transfer in mixtures of oxides in rare gases have been at pressures below 250 Torr. However, experiments on rare gases suggest greater efficiencies of production of excited states at higher pressures [4] and we have therefore planned kinetic studies to pressures of 30 atm. At high pressures, small impurity levels have been found to rapidly quench excited states [5,6]. Our current cell uses standard ultrahigh-vacuum techniques. By baking to 400°C at 10^{-9} Torr, very high purities are achieved. In addition, the rare gases used are cleaned in an ultrahigh-vacuum titanium furnace with a resultant impurity level of less than 1 ppm. With the closed cell required for these high pressures, difficulties maintaining the dopant gas composition can occur, limiting the time duration of studies on a single sample. We are now building several diagnostic systems for monitoring gas composition during the experiments.

In addition to the previously mentioned construction, preliminary measurements on oxide mixtures were initiated. For these measurements the electron accelerator provided a continuous current of 1μA at 150 KeV. 1/2 meter visible and VUV scanning monochromators, associated optics and cooled photomultipliers were used to monitor the spectra. In the middle of the past year, the electronics necessary for pulse counting were completed and a significant improvement in signal-to-noise ratio and sensitivity over previous results using phase-lock-loop techniques were achieved. The visible system was absolutely calibrated using an Optronic Laboratories tungsten ribbon lamp. Spectral surveys of N_2O in Ar, O_2 in Ar and O_2 in Ne were completed.

3. RESULTS FOR MIXTURES OF O_2 IN ARGON

Shown in Fig. 1 is the spectra of the O('So) → O('D_2) transition at 5577Å. The shape of the line core was found to be independent of argon pressure over the range 180 - 8500 Torr, suggesting predominately free-free rather than bound-free transitions [7]. At very high sensitivities a banded structure in the wings of the O('So) line may be an indication of bound-free transitions which have been previously observed in Argon-oxide mixtures [8].

Weak bands in the region 3700 - 4500Å were noted and attributed to the O_2 $B^3\Sigma \rightarrow X^3\Sigma$, ground state (Schumann-Runge) transitions. With increasing O_2 density, there also appears to be enhancement in intensity of the 1900Å band which is present in pure argon. The specific assignment of this band in pure argon is uncertain [9], and hence it is difficult to speculate on the cause for enhancement. This increase in 1900 Å intensity might also be explained by an as yet unidentified transition. The possibility of a second transition will be determined by the future time dependent study.

The intensity of the 5577Å transition as a function of argon and O_2 densities is shown in Figs. 2 and 3, and that of the 1250Å band due to Ar_2* transitions, in Figs. 4 and 5. Ar_2* is known to be formed in the three-body reaction [5,6],

$$Ar^* + 2\,Ar \rightarrow Ar_2^* + Ar\,, \qquad (1)$$

and we have verified the linear dependence of the Ar_2* radiation on argon pressure predicted for the conditions of this experiment.

The O('So) intensity varies at low pressures as the argon pressure to the 3/2 power, and at higher pressures as the pressure squared. At the highest pressures of argon (11 atm) it appears to become constant. Experiments at higher pressures will be done to verify this effect. These results contrast with those of previous authors who claim a linear increase with added rare gas [10]; however, these have been in experiments at low pressures (<250T), or in systems where the impurity levels are not as carefully controlled. An additional explanation may be the affect of dissociation products of O_2 on the formation and quenching of reactions leading to O('So) production. Since this is a closed cell experiment, care must be taken to include the affect of any such products. A mass

spectrometer and laser absorption system now being installed will monitor impurities and dissociation products.

The dependence of O('So) intensity on O_2 concentration is particularly pronounced and indicates the reaction mechanism to be highly sensitive to this parameter. The initial constant intensity shown in Fig. 3 is probably due to a small (< 1 ppm) residual of O_2 in the argon.

The simplest kinetic model one can postulate to explain population of the O('So) level is that of collisional dissociation by excitation transfer from bound, excited argon molecules:

$$Ar_2^* + O_2 \rightarrow O\,('So) + O + 2Ar\ . \qquad (2)$$

This reaction is probably insufficient to explain our results since it implies a linear dependence of O('So) on Ar concentration.

It is of special interest to determine the quantum efficiency for energy transfer from Ar_2^* to O('So) (if this is the major transfer mechanism to O('So)), since this will determine in large part, the overall efficiency of any argon-O_2 laser amplifier. Even though it is not practical at this time to absolutely calibrate our VUV Optical system, by making some reasonable estimates of various VUV optical components and utilizing the absolute calibration of the visible system, we were able to estimate the absolute efficiency of the VUV at 1250Å. By assuming that reaction (2) is the major quencher of Ar_2^* we have determined that at 150 PSIG Ar and an O_2 number density of approximately $1 \times 10^{16}/cm^3$, that the quantum efficiency for excitation transfer from Ar_2^* to O('So) is $40.3\% \pm 17.7\%$. Here we also assume de-excitation of O('So) proceeds only by O_2 quenching and collisional radiation. Hence our estimate is a lower limit, in that both O_3 and ground state oxygen, which are possible reaction products for this experiment, have larger deactivation rates of O('So) than does O_2 [1].

4. MIXTURES OF N_2O IN ARGON

This series of experiments gave results comparable to that of O_2 in Argon indicating that N_2O very rapidly dissociates into N_2 and O_2. Small amounts of NO are also produced since the NO γ bands were weakly present.

We attempted to measure the rate of N_2O dissociation by monitoring the time dependence of spectral features in fresh mixtures for times following initial excitation by the electron beam. Since intensities did not vary after a few seconds from initial excitation, dissociation to an equilibrium configuration is rapid. Mass spectrometer analysis of gas composition is necessary for a proper understanding of the kinetics of these mixtures in future experiments.

5. MIXTURES OF O_2 IN NEON

No O('So) radiation was observed in these experiments, indicating that the energy difference between Ne_2^* and O_2 is too large to allow for rapid collisional excitation transfer. Weak O_2 Schumann-Runge bands were observed.

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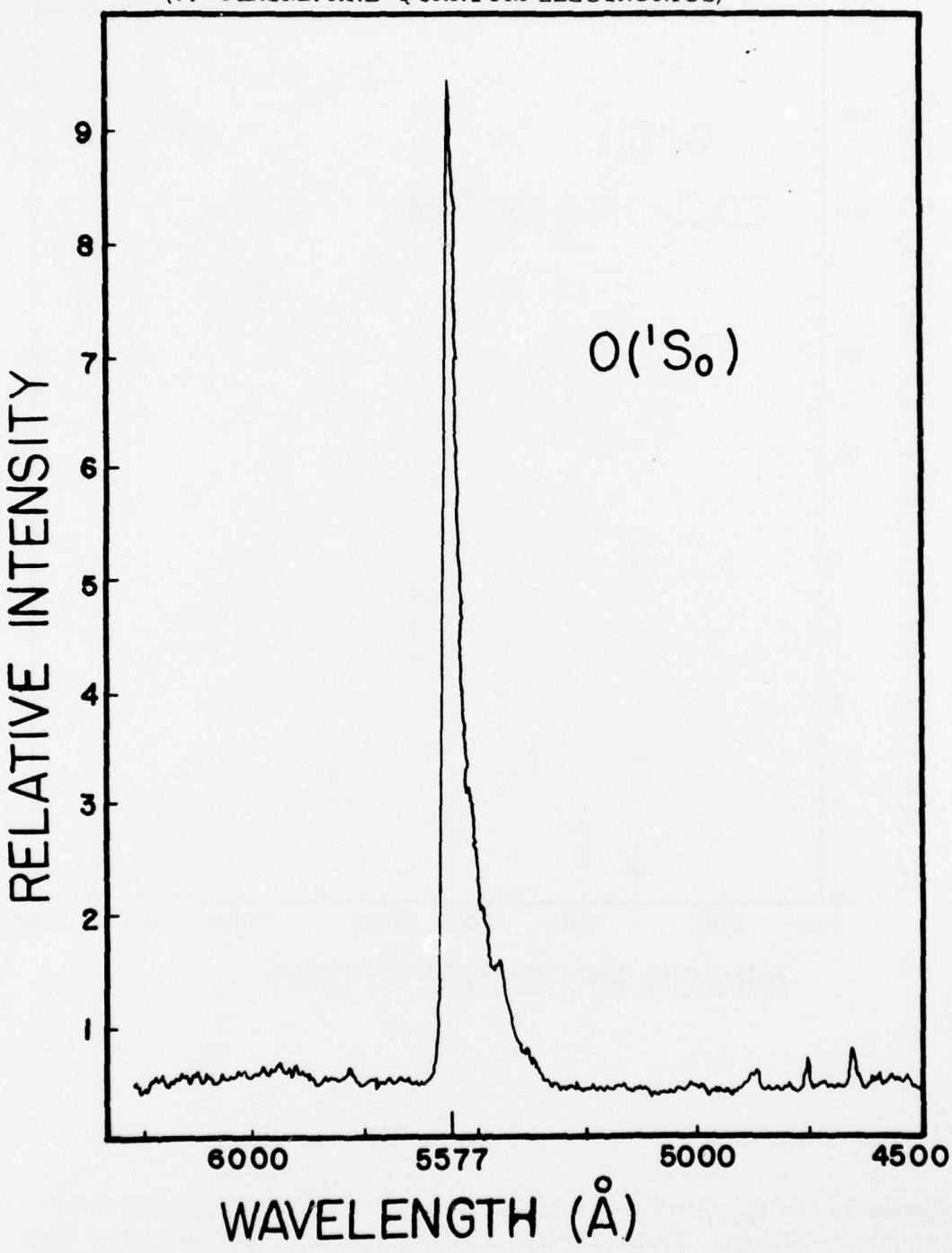

Figure 1. Spectra of $O('S_0)$ Taken at 850T Argon and 1.715T O_2.

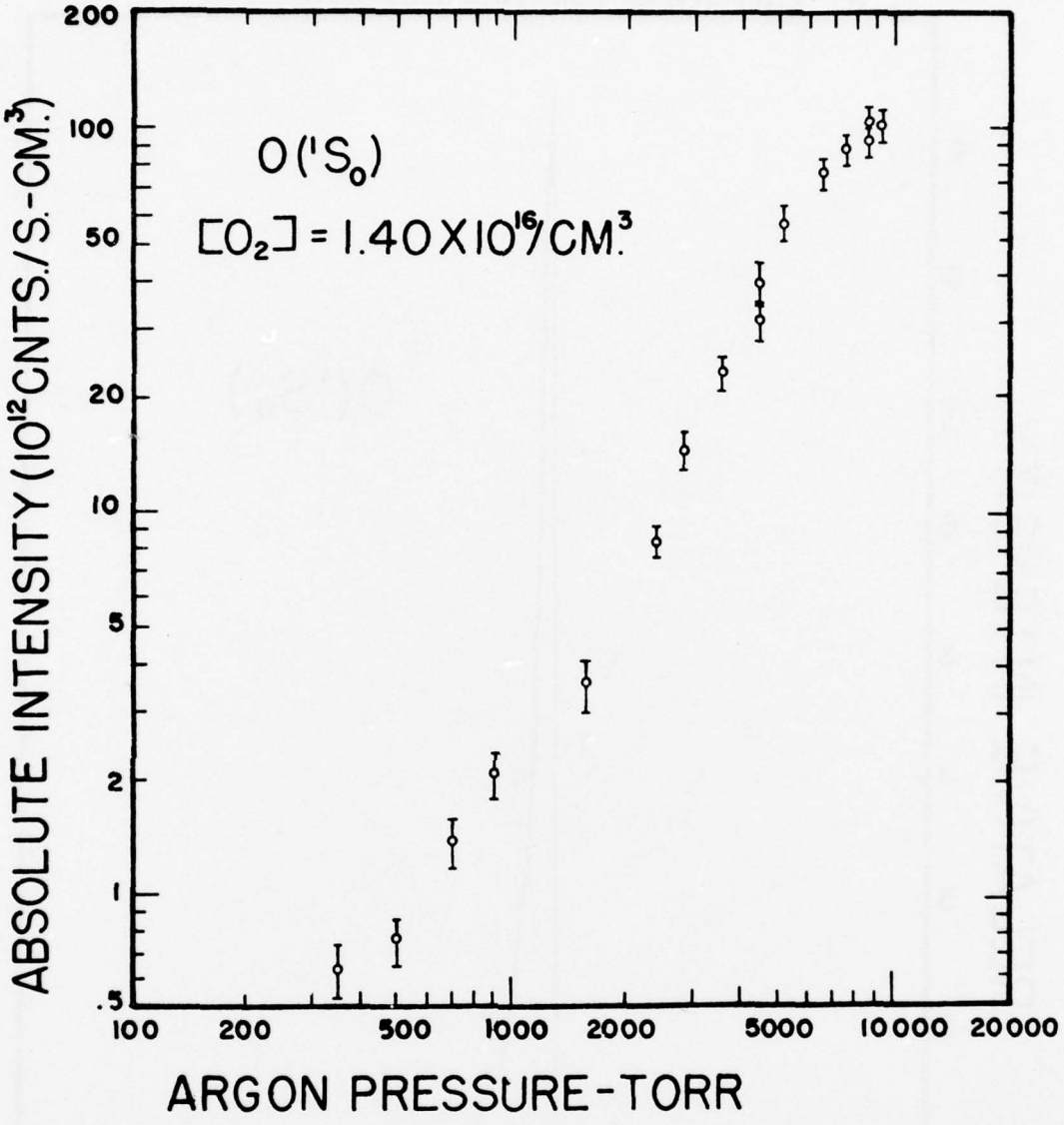

Figure 2. $O('S_0)$ Absolute, Integrated Intensity is Shown As A Function of Argon Concentration at Fixed O_2 Concentration. The Error Bars Represent Both Uncertainty in Absolute Calibration and in Statistical Deviation.

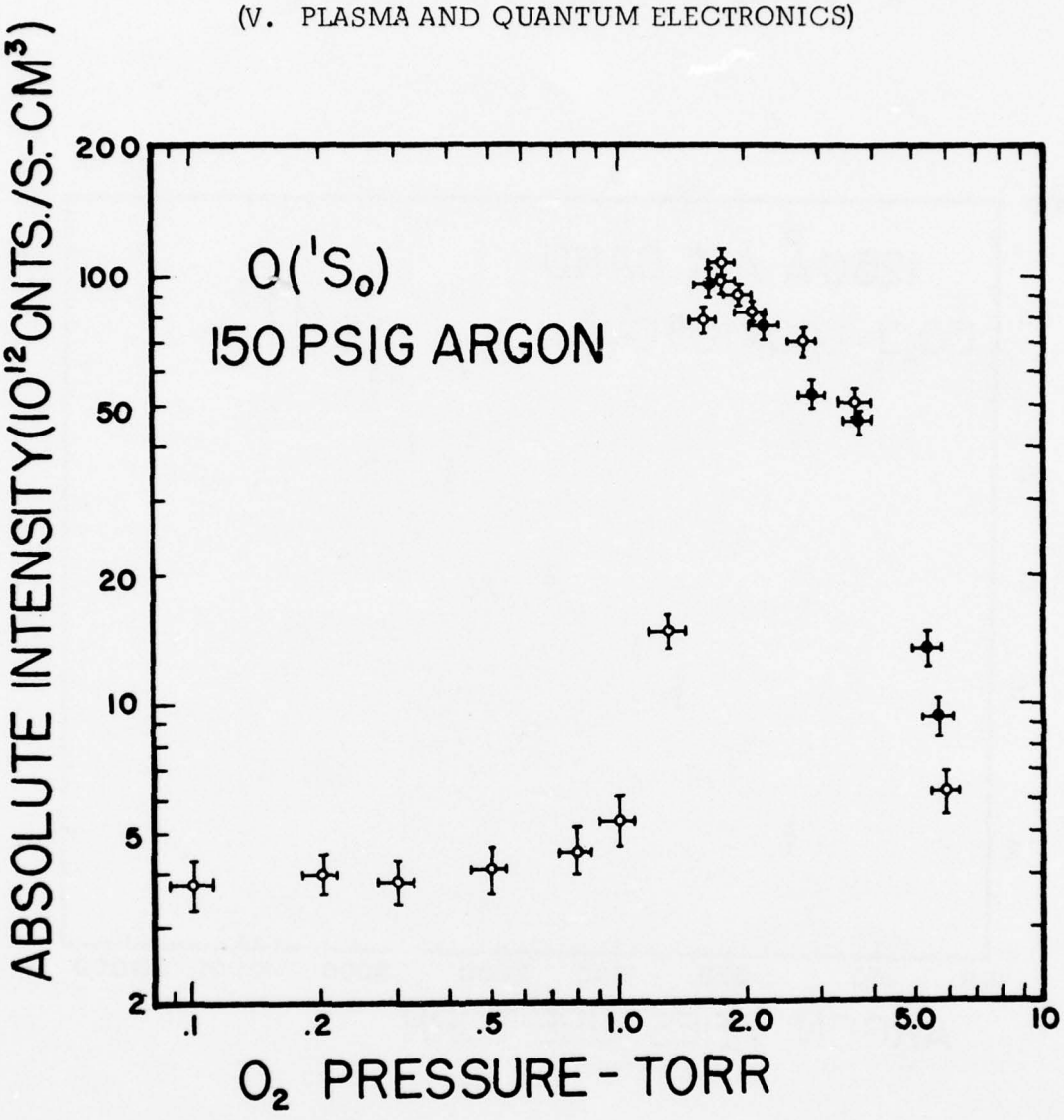

Figure 3. $O(^1S_0)$ Absolute, Integrated Intensity As A Function of O_2 Concentration at 150 PSIG Argon. The Vertical Error Bars Represent Uncertainty in Absolute Calibration and Statistical Deviation While Horizontal Error Bars Represent Cumulative Error Due to Repeated Doping.

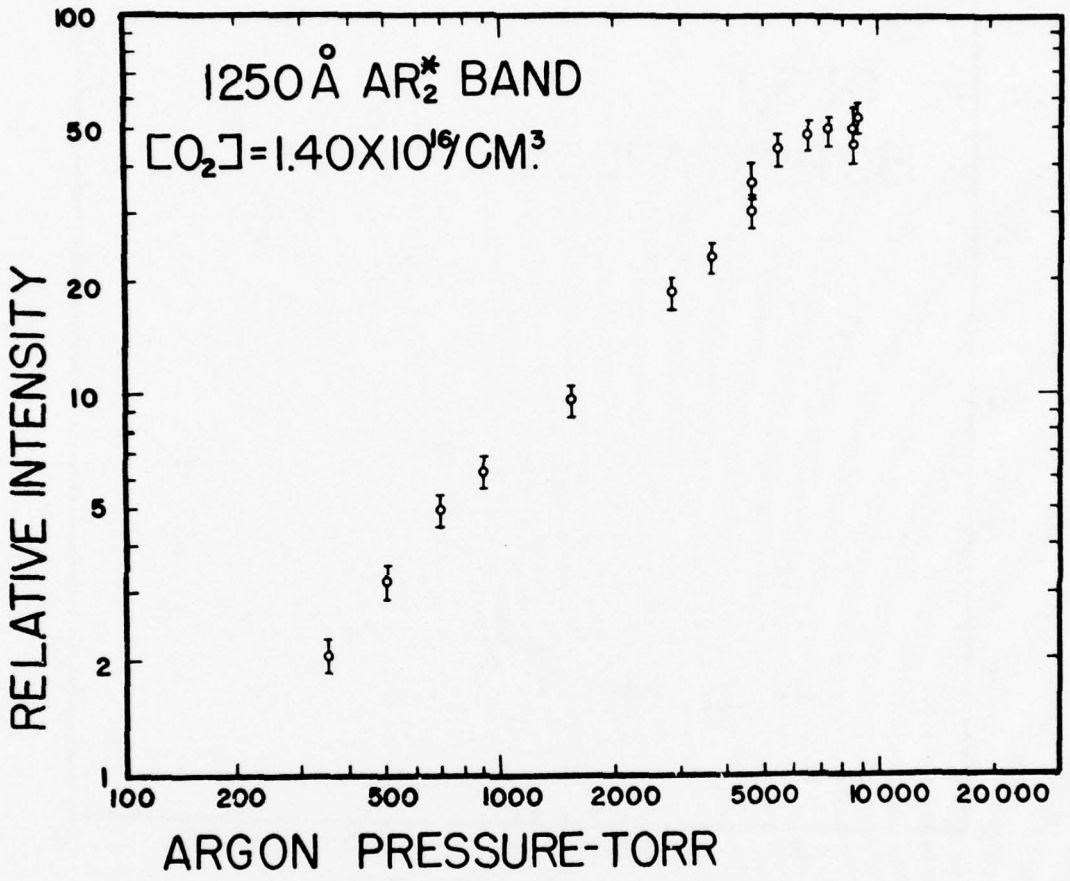

Figure 4. The Integrated Intensity of the 1250Å Ar_2^* Band Is Given As A Function of Argon Pressure at Fixed O_2 Concentration. The Intensity Scales In This Figure and Fig. 5 Are the Same.

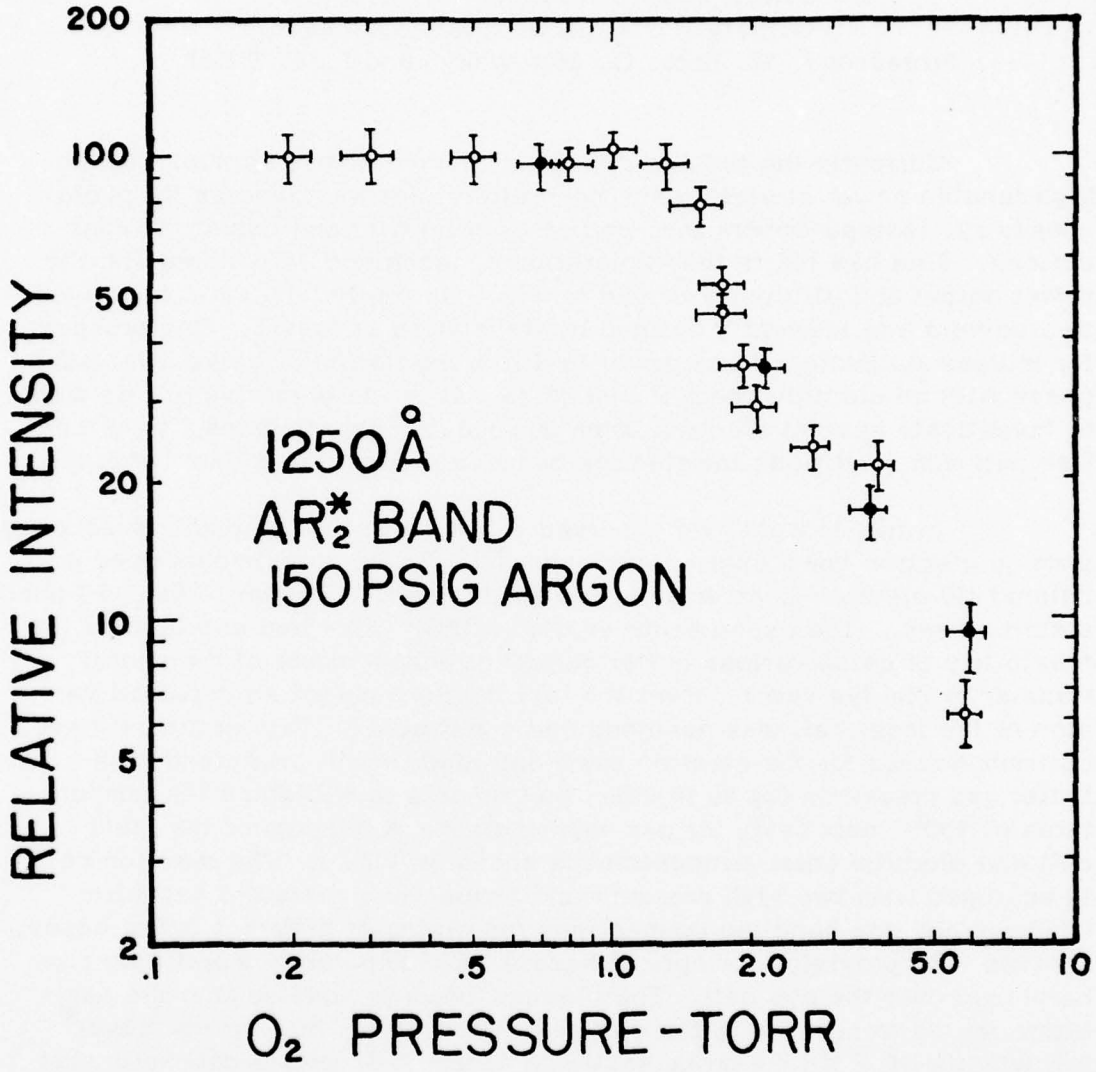

Figure 5. Integrated Intensity of the 1250 Å Ar_2^* Band Is Given As A Function of O_2 Pressure At 150 PSIG Argon.

G. ELECTRON BEAM EXCITATION STUDIES OF POTENTIAL DYE VAPOR PHASE LASERS †

Professor J. W. Keto, G. Morowsky, and F. K. Tittel

Currently the tunable dye laser is used nearly exclusively for high tunable power at visible and near-ultraviolet wavelengths for photochemistry, isotope-separation, and other scientific and industrial applications. This has led to the exploration of techniques for increasing the power output and efficiency of dye lasers. Currently, dyes are dissolved in a solvent and indirectly pumped by flashlamps or lasers. One prospect for increased efficiency and power is direct excitation of a dye in a vapor phase with an electron beam or discharge. It is the objective of this work to investigate several electron beam pumped dye vapor systems to establish optimum conditions for electron beam excited vapor-phase dye lasers.

In initial work, we observed for the first time strong fluorescence from an electron beam excited dye vapor [1]. These experiments used a Pulsrad 110 electron-beam accelerator producing a 0.75 Mev, 20kA, 20 nSec electron beam. The experiments studied POPOP vapor and established the feasibility of using various buffer gases for enhancement of the energy transfer to the dye vapor. Over the last contract period an improved version of the laser cell was designed and constructed. This cell must have optimum access for the electron beam and laser beam, withstand high buffer gas pressures (up to 10 atm), and be able to withstand the temperatures of 450°C necessary for dye vaporization. A diagram of the laser cell and electron beam arrangement is shown in Fig. 1. The reaction cell is equipped with two high pressure and temperature resistant sapphire windows and gas handling connections for mixing of different buffer gases. An oven with provision for optical access and temperature monitoring can be placed over the dye cell. The electron beam is coupled into the excitation region transverse to the optic axis through a 25μm thick Havar® foil window of 8 x 1 cm cross sectional area. A Rogowski coil surrounds the graphite cathode for monitoring the electron beam flux. Technical details of the cathode-anode construction are show in Fig. 2. From the

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burn pattern on the Havar foil, it could be established that a knife-edge shaped cathode placed 12 mm from the anode window produced a very narrow excitation profile. In order to optimize the performance of the electron beam accelerator it was necessary to establish a compromise of relatively long life-time for the anode foil, effective electron beam transmission through the anode foil and optimum impedance matching of the diode to the Blumlein discharge network of the electron beam accelerator. With an anode-cathode spacing of 12 mm, reliable results were obtained for at least 20 shots of the accelerator. The optical emission of the dye vapors was monitored simultaneously by a grating spectrograph and a fast-risetime Valvo UVHC 20 photodiode whose output was observed on a Tektronix 7904 oscilloscope. In order to differentiate between the pump radiation of the buffer gas and the dye fluorescence suitable cut-off filters were used.

We have studied in detail the excitation process of three selected dyes, POPOP, p-terphenyl, and the xanthene dye N-92 by monitoring the electron beam excited fluorescence of (i) the pure dye vapor, (ii) a dye vapor with a rare gas buffer such as xenon, and (iii) a dye vapor with a buffer gas which can produce u.v. laser emission such as $Kr + NF_3$ [2], $Xe + NF_3$ [3], and $Ar + N_2$ [4]. The following sections describe results for each dye.

1. ZANTHENE DYE N-92

Zanthene N--92 is selected as a potential lasing dye because its absorption band perfectly matches the emission range of the $Ar + N_2$ and $Xe + NF_3$ systems. Electron-beam excitation of N-92 dye vapor revealed intense fluorescence whose dependence on vapor pressure as derived from temperature measurements is plotted in Fig. 3. A slight saturation is evident at temperatures approaching 380° C. At this temperature, breakdown of the molecular structure seems to occur. This transition is irreversible, since the fluorescence does not reaapear at lower temperatures. This observation is in agreement with a proposed explanation for the observed discontinuity in the vapor pressure curve of this dye by Schäfer and Steyer [5]. Furthermore, Fig. 5 shows that the N-92 fluorescence increases more than 10 fold in the presence of Xe buffer gas. From Fig. 5 we may also conclude that collisional energy transfer from Xe to the dye is more efficient than radiation transfer from known rare gas-halide laser mixtures, such as XeF[3] or $Ar-N_2$[4]. The XeF laser

mixture was prepared according to Ref. 3 by using a mixture of Ar, Xe, and NF_3 in the ratio of 250:25:1 at a total pressure at room temperature of 1 atm. The presence of XeF obviously enhances the N-92 fluorescence to a higher degree than expected from the Xe content of the mixture as compared with the addition of pure Xe. This may be partially due to the large amount of Ar present, which has been proven to be nearly as effective in energy transfer as Xe. Compared to XeF, $Ar-N_2$ mixtures are less effective in generating the N-92 fluorescence intensity as a function of Xe pressure. As shown in Fig. 4, the dye intensity increases with increasing xenon pressure reaching a maximum at p = 2 atm. There are several possible kinetic models which explain this behavior; and we are currently trying to determine experimentally which one is most probable.

2. POPOP

The most promising dye in the vapor phase investigated by us so far is the dye POPOP [p-phenylene-bis-(5.-phenyl-2.-Oxazole)]. It is photochemically stable at elevated temperatures which is a prerequisite for long-term laser operation and its fluorescence peak for a dye vapor-buffer gas mixture is centered around 390 nm. The fluorescence intensity, observed within the spectral range of 30 nm centered at 360 nm, is plotted as a function of vapor pressure for pure POPOP vapor and various buffer gases in Fig. 5, apart from the linear increase of the POPOP fluorescence with POPOP vapor pressure up to 30 torr. It is interesting to note that the KrF supported dye fluorescence breaks down completely at higher vapor pressure. This behavior is probably a consequence of the small amount of NF_3 present in the system (He, Kr, and NF_3 were mixed in a ratio of 500:50:1 according to Ref. 2 with a total pressure of 1 atm), which can no longer compete with the high pressure of POPOP. In addition to shielding of the resonant energy transfer in the rare gas-halide system by the presence of appreciable amounts of dye vapor, the addition of He finally quenches the dye fluorescence as shown by the reduced fluorescence intensity of the system POPOP + He (cf. Fig. 8 and Fig. 3 of Ref. 1).

3. P-TERPHENYL

p-terphenyl has a fluorescence range which covers the potentially useful 300 to 360 nm range of the UV spectrum and is convenient to use in the vapor phase due to its high vapor pressure. It was found (Fig. 6) that the weak fluorescence of pure p-terphenyl vapor, compared to the dyes N-92 and POPOP, could not be enhanced to the same degree of brightness by the addition of a KrF mixture and other buffer gases. In fact, as soon as the dye vapor pressure exceeded 40 torr corresponding to 270°C, the intense KrF radiation was quenched completely, as observed previously for the POPOP:Ar-N_2 mixture [1] and for POPOP:KrF. Even the presence of pure Xe gas, which exhibits the most effective buffer gas properties in the case of the two other vapor phase dyes, led to saturation of the p-terphenyl fluorescence, although the de-excitation energy of the Xe_2 dimer (7.2 eV) matches better the required singlet state of p-terphenyl compared to the other dyes investigated. This might be a consequence of an increased intersystem crossing rate k_{ST} in p-terphenyl due to the large heavy-atom effect of Xe.

The successful generation of intense dye vapor fluorescence by relativistic electron bombardment via a suitable buffer gas demonstrates the feasibility of electron beam pumping of complex organic dyes in the vapor phase. From the spectral profile of the fluorescence of the three dyes studied so far with an ultraviolet absorption range from 220 to 390 nm, details of the energy transfer mechanism for the xenon buffer gas can be inferred. A close energy match of the dye vapor absorption peak to the de-excitation energy of the Xe_2^* excimer (7.2 eV) does not appear to be essential, since this would, in fact, suggest that p-terphenyl would fluoresce stronger than POPOP (singlet-singlet transition energy 3.8 eV) or N-92 (singlet-singlet transition energy 3.1 eV). However, the strong fluorescence intensity obtained for electron beam excited N-92 indicates that the electron stopping power of xenon (the rare gas used in these experiments with the highest atomic number) makes it an attractive buffer gas. The feasibility of enhanced excitation of the dye vapors through radiation transfer from rare gas halide excimer systems was examined in some detail. However, quenching of the excimer fluorescence by the dye vapor seems to preclude any significant amount of radiation transfer.

Of all the mixtures studied, only N-92 and Ar-N_2 mixtures seem to show partial radiative energy transfer. This may be due to the fact that the buffer gas mixture contains a higher concentration of the minor component (N_2) as compared to the fraction of NF_3 in the rare gas mixtures.

In summary, the optimum conditions for spontaneous emission of electron-beam excited dye vapor-buffer gas mixtures in our experimental arrangement have been established. The presence of xenon gas at a pressure of about 2 atm appears to produce the best fluorescence enhancement. So far, internal radiation transfer processes have not been effective in the excitation of vapor phase dye lasers, since the presence of even small amounts of dye vapor inhibits the excitation mechanisms of the efficient rare gas halide excimer systems. Work is now in progress to establish the feasibility of electron beam-pumped vapor phase dye lasers based on these experimental observations.

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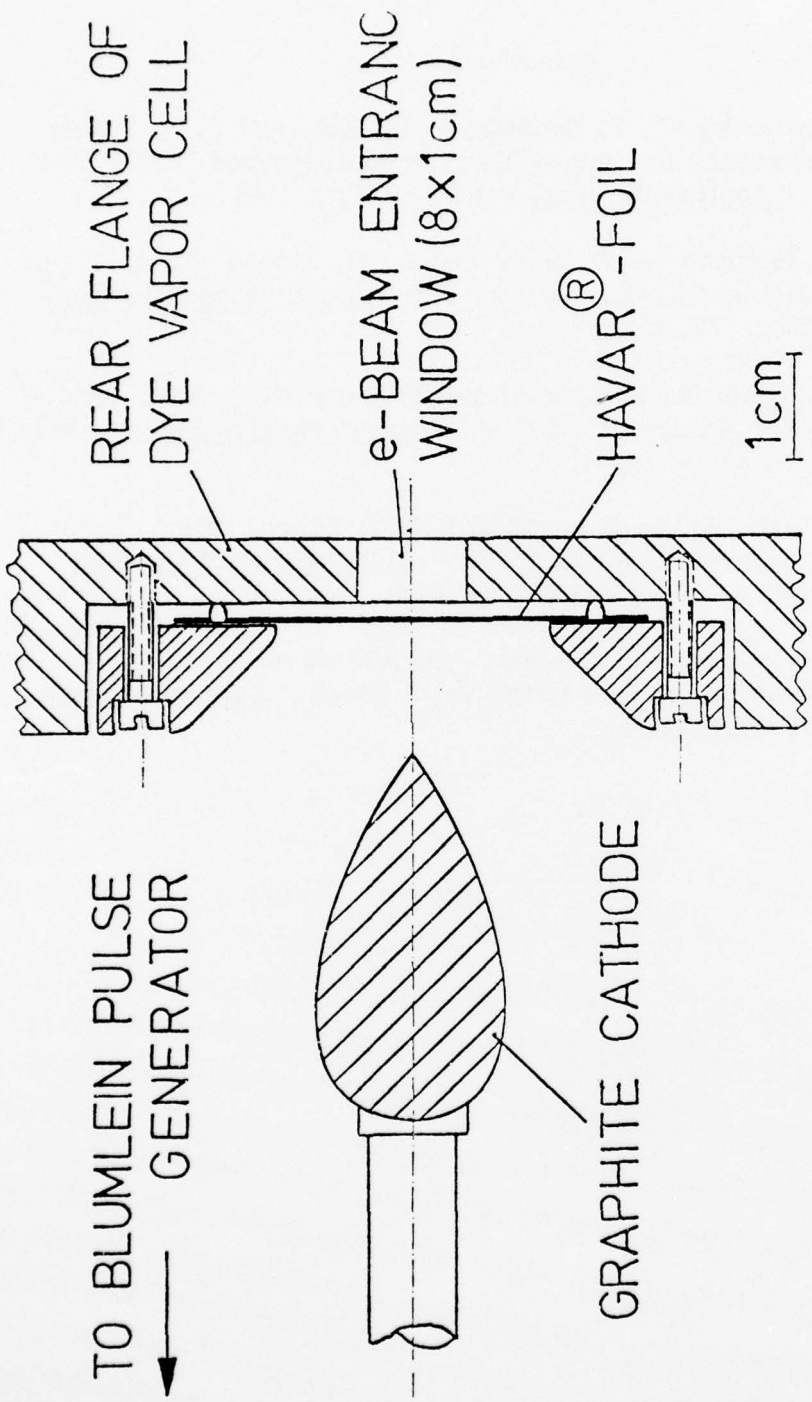

Figure 1. Schematic Diagram of the Apparatus.

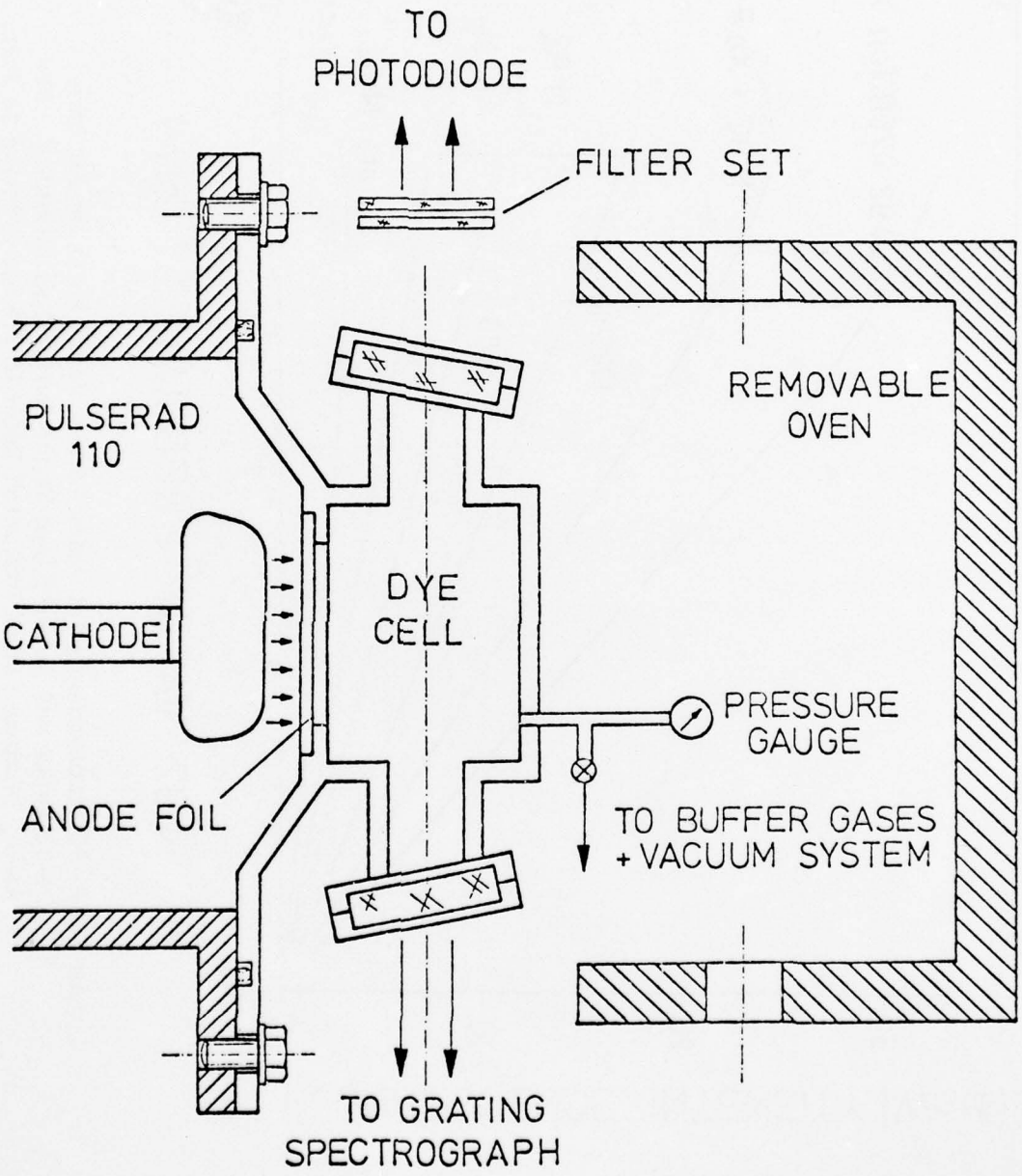

Figure 2. Technical Details of Field Emission Diode of Electron-Beam Accelerator.

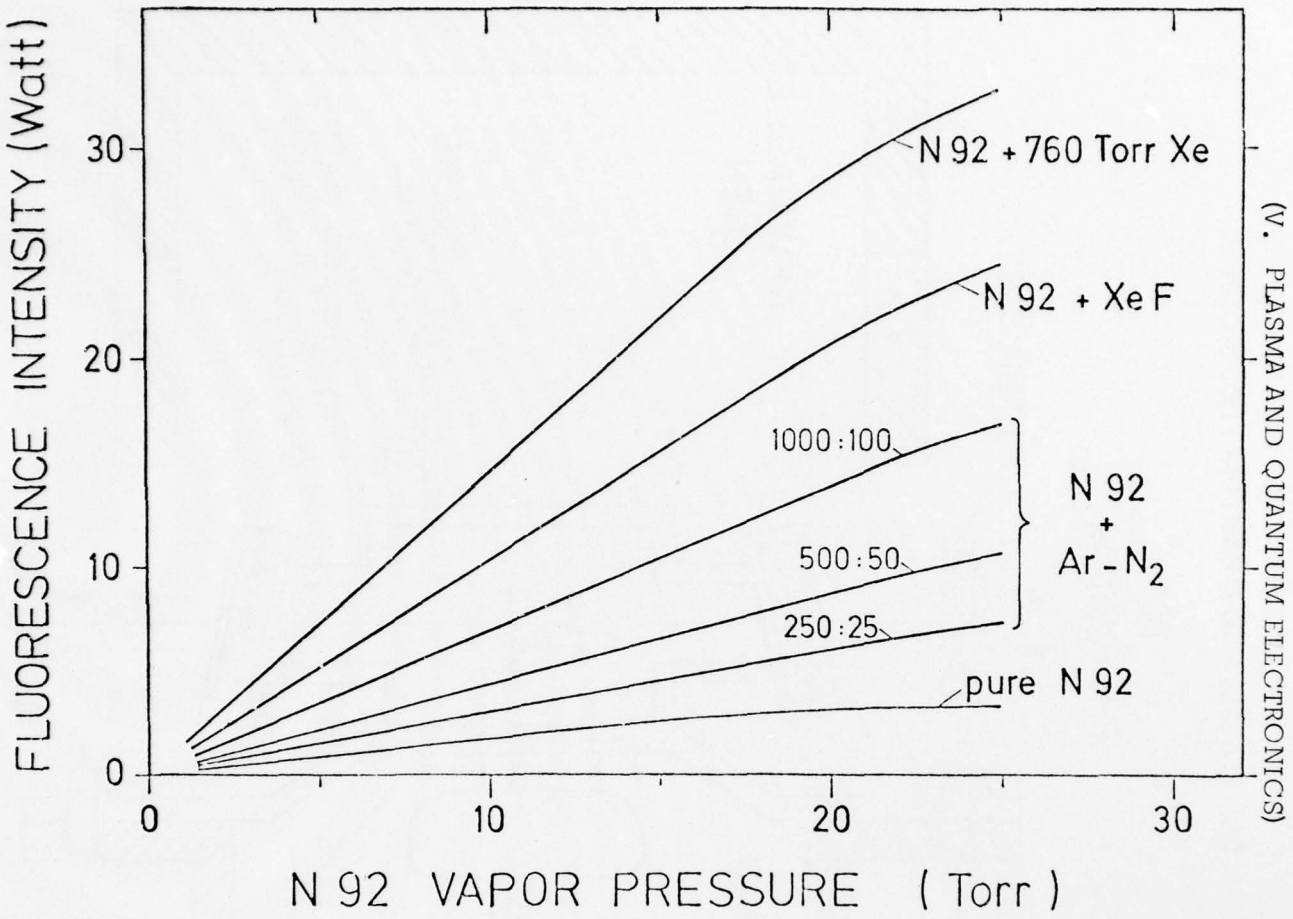

Figure 3. N-92 Fluorescence Intensity Versus Vapor Pressure for Pure N-92 Vapor and Several Dye Vapor-Buffer Gas Mixtures. The Ar-N_2 Mixture Ratios Indicated Refer to Pressure Ratios in Torr.

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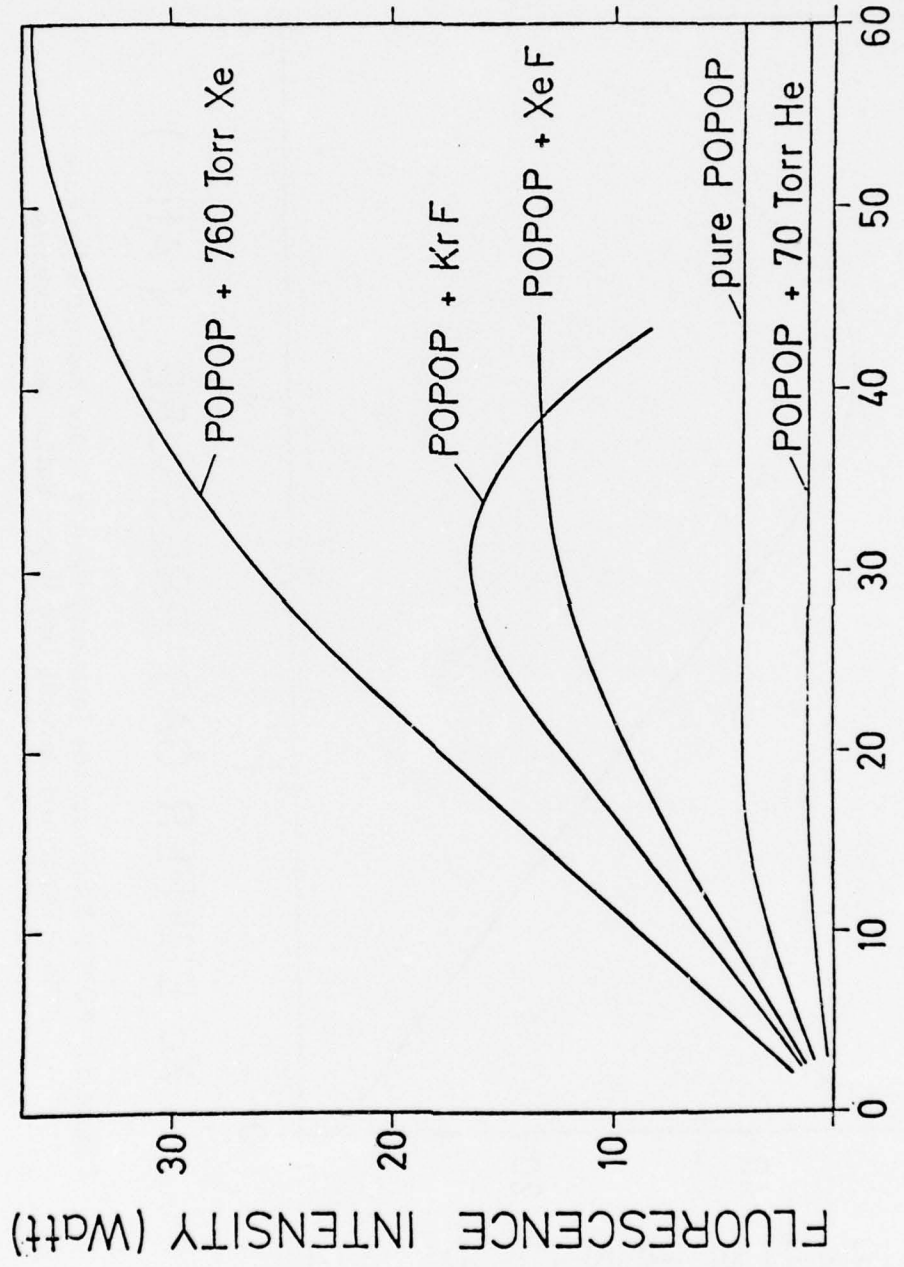

Figure 4. Saturation Behavior of N-92 Fluorescence in the Presence of Xe Buffer Gas.

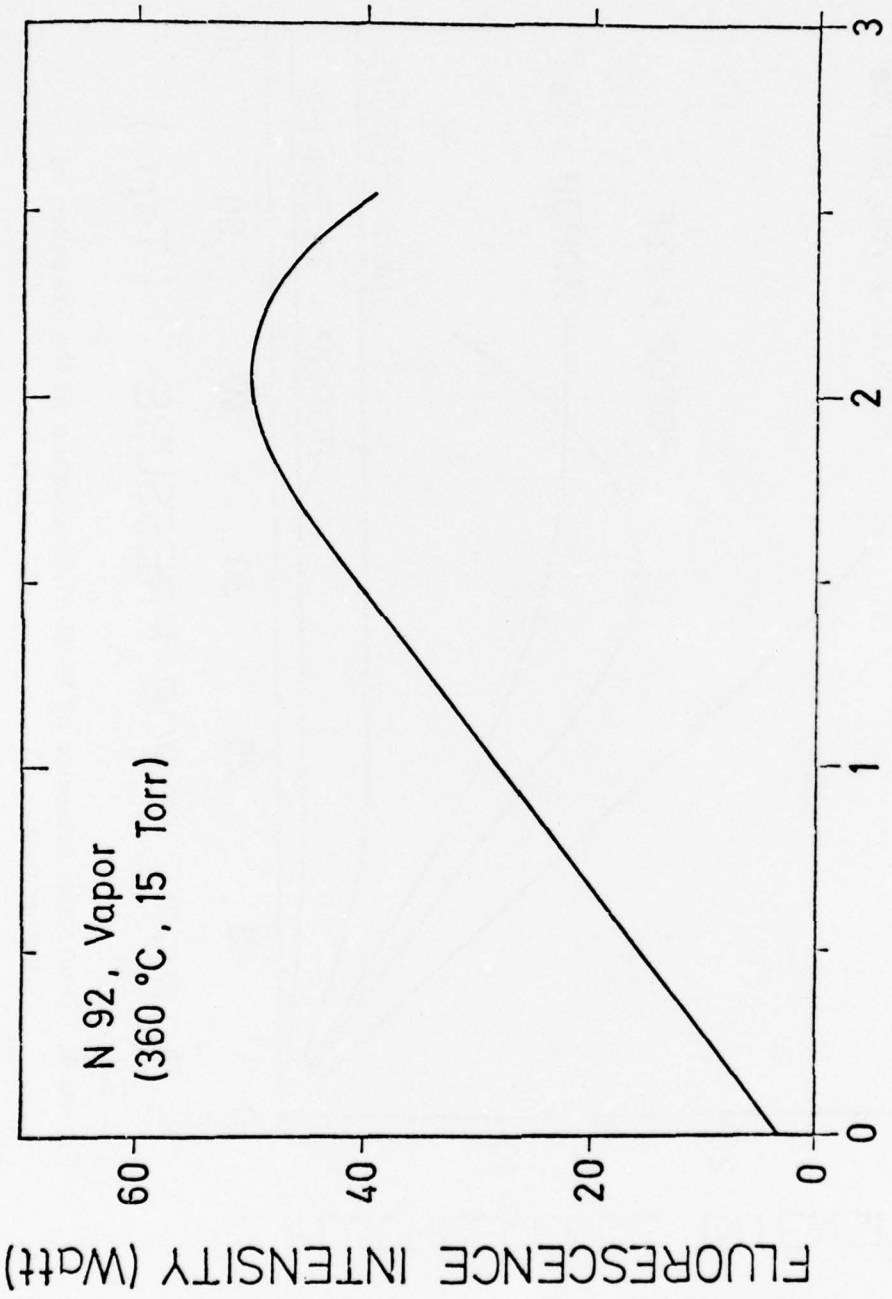

Figure 5. POPOP Fluorescence Intensity Versus Vapor Pressure for Pure POPOP Vapor and Several Dye Vapor-Buffer Gas Mixtures.

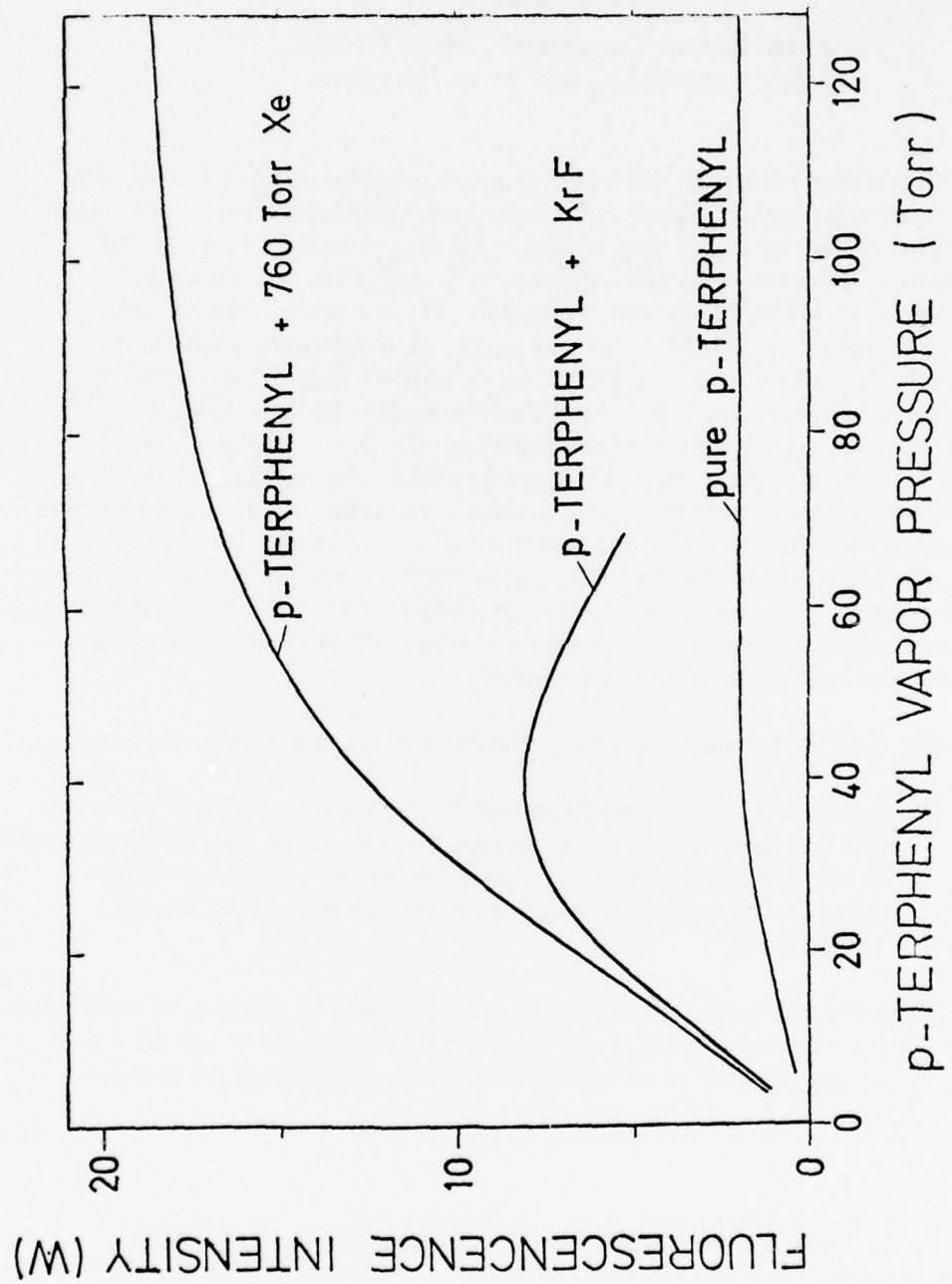

Figure 6. Normalized Absorption and Fluorescence of P-Terphenyl in Cyclohexane Solution[20] with Spectral Position of KrF Laser Line Indicated.

H. COLLISION-INDUCED SCATTERING OF LASER LIGHT †

Professor Lothar Frommhold, Mike Proffitt,
Mark Barrington, and T. D. Raymond

The major effort of the laser light scattering work is directed toward the measurement of absolute scattering intensities of collisional pairs of atoms of the heavier rare gases. By direct comparison of our collision-induced Raman spectra of the rare gases with various well-studied spectra of nitrogen [1] and hydrogen [2], we were able to obtain a number of calibration points. For example, at a frequency shift of 12 cm^{-1}, and at a temperature of 24°C, each pair of argon atoms scatters an amount of laser light per 1 cm^{-1} bandwidth equivalent to 2.58×10^{-18} nitrogen molecules in the pure rotational line $J = 2 \rightarrow 0$ at 11.94 cm^{-1}, if irradiated with the same power. This information can readily be used to obtain scattering cross sections, the photoattenuation coefficients versus pressure, or all similar basic light scattering data desired [1]. This calibration in argon could be shown to be valid over a gas density range from essentially zero to at least 15 amagat. We believe that such measurements have not been reported before. Presently, attempts are being made to further improve the accuracy of these numbers.

We feel that these data are significant for the following reasons:

(1) In this way, the magnitude of the anisotropy of the polarizability tensors of the rare gas atomic pairs can be determined, which are not sufficiently well known at present. (This aspect of the work is supported by the Robert A. Welch Foundation).

(2) Such measurements can be readily used to predict accurately the attenuation of laser beams in dense gases, as far as it is due to collision-induced scattering of pairs of atoms.

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It was pointed out by Gerardo [3] that for every light scattering process there is a corresponding stimulated scattering process which might well determine an upper level of the power density for gas lasers, as well as for the propagation of high-powered laser pulses through dense gases. A thorough understanding of the collision-induced light scattering processes of atomic pairs hence appears to be of interest.

At the highest gas densities (for argon above about 12 amagats) our spectra showed at the lowest frequencies ($\sim 3\ cm^{-1}$) an enhancement, which was not expected on the basis of the theories of collision-induced spectra of binary pairs. We were now able to show that this new feature of the spectrum does have a simple explanation: it is produced by the far wings of the so-called intra-collisional process predicted by von Kranendonk [4] some time ago. In other words, since subsequent collisions of the same atom produce another time-modulation of the dipole moment induced by the laser field, there is a pressure-dependent broadening mechanism superimposed with the collision-induced scattering of isolated pairs. This intercollisional scattering gives rise to a Lorentzian-like profile of a width proportional to the pressure. The far wings of this Lorentzian begin to show up in our experiments at high pressures.

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I. ELECTRON SCATTERING FROM ATOMS AND MOLECULES†

Professor Manfred Fink and M. Kelley

During the last year research was carried on in three different areas: (1) determination of charge density distributions in atoms and molecules from our electron diffraction data; (2) the thermodynamics and composition of nonvolatile compounds like inorganic salts and metals; and (3) intramolecular energy transfer among various vibrational modes observed by superelastic electron scattering. The above projects are listed in order of their degree of completion.

With our electron diffraction unit we have added to the N_2 data new CO and O_2 results. The density maps have been constructed with the technique described in [1]. However, this approach is plagued with several approximations. We have significantly improved the evaluation, and the new maps are presenting distribution functions from which we expect to derive several moments which can be compared with optical measurements. In the course of the density studies it became apparent that our diffraction unit is also capable of recording the data precise enough that the molecular structure parameters can be derived with unprecedented accuracy. In order to learn the limit of counting machines as a new and more advanced structure tool, we engaged in a detailed study on the data correlation as it applies to our results. The results are very important to structural chemistry, as well as for the structure determinations of amorphous thin films. The results are as follows:

Table 1. Structure Analysis of CF_4.

	Data Without Noise	Data With Noise	Previous Results
r(C-F)	1.3325 ± 0.0003	1.3318 ± 0.0006	1.323 ± 0.005
ℓ(C-F)	0.0437 ± 0.0015	0.0466 ± 0.0024	0.049 ± 0.005
r(F···F)	2.1830 ± 0.0002	2.1830 ± 0.0004	2.160 ± 0.005
ℓ(F···F)	0.0586 ± 0.0010	0.0595 ± 0.0017	0.059 ± 0.005
Standard Deviation of Fit	0.0018	0.0031	

†This research was supported in part by the Joint Services Electronics Program under Contract F44620-76-C-0089 and in part by the Robert A. Welch Foundation.

It is obvious from Table 1 that our data is about one order of magnitude more precise than previous results. However, even we had to add artificial noise to cover up data correlation. Since the completion of these series, we have improved the diffraction unit by adding an optical encoder to record the angles. We hope that the next data series will prove that our efforts have been worthwhile, and a genuine, uncorrelated set can be recorded.

A second group of questions has been answered by our last year's efforts. Every scattering record claiming precision in the .1% range has to be discussed from the point of view of the influence of the finite scattering geometry. In an actual experiment, the counted events originate from an extended scattering volume, defined by the volume common to the electron and gas beam, and the detector which subtends a definite acceptance cone. We have calculated in a computer experiment the extent to which a model cross section will be distorted due to the averaging. We selected the range of parameters as they apply to our unit. The results however, proved to be of such general nature, that requests of our peers indicate that it is desirable to publish the method and the conclusions, and to make the numerical results available through a technical report.

High energy electron scattering research has been funded for many years by JSEP. However, our results have found such enthusiastic response that we feel that there is a very good chance now that the program might be picked up by NSF. To this end, we have written a two-year $100,000 proposal. If the funding is approved, we intend to switch the JSEP money to a new experiment which we are presently developing, and which is outlined below.

Due to the infrared lasers (CO_2, HF and others) an old topic became very interesting again: the behavior of molecules after they are excited into high-lying vibrational states. The question of mode coupling, even the meaning of a mode, is no longer so easy to determine compared to those modes lying deep in the potential well of the electronic ground state. It is our intent to excite several molecules with various lasers and follow the internal relaxation mechanisms with low energy electrons. These electrons act as perturbers and cause the molecule to relax. The excess energy is transmitted to the electron, which will arrive at the detector with more energy than when it started from the electron

gun. This is analogous to the anti-Stokes lines in Raman scattering. The phenomena has been studied for an electronic transition of Na by Hertel and Stoll [2]. Similarly, as in our electron diffraction success, we intend to develop a new technology (the superelastic scattering from vibrationally hot molecules), and thus truly contribute to the deeper understanding of the energy transfer within molecules. We might be too late to contribute to the successful completion of laser isotope separation or laser plasma heating, but we will help understand why certain processes work and why others will not. This is not just an esoteric idea, but we have worked in low-energy electron scattering for some time, and we think the prospect has a great enough chance of success that the challenge should be accepted and brought to a productive stage.

To this end we obtained through the government surplus program, a $30,000 stainless steel vacuum chamber complete with the 10" diffusion pump and 30 cfm rotary pump. We have built a triple set of Helmholtz coils to compensate the magnetic field of the earth to less than 1 m Gauss. At present we are building an electron gun which hopefully, due to its new electron optical system, has no anomalous energy spread, and should therefore deliver a strong monoenergetic electron beam after the exit slit of the spherical monochromizer.

The third project we are working on is funded by the Robert A. Welch Foundation. The questions we try to answer are directed toward the molecular structure of nonvolatile compounds. This project was funded in the first two years by JSEP, until the Robert A. Welch Foundation supplied continuing funds. We have at present focused on rock salts and are continuing to measure, with our quadrupole mass spectrometer, the reaction constant of dimerization. The nozzle temperature is constant to .5°C and the mass spectra are calibrated through a background gas mixture of Ne, Ar, Kr and Xe.

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J. LOW ENERGY MOLECULAR BEAM MACHINE †

Professor W. W. Robertson, Professor L. Frommhold, and Georges Jamieson

The molecular beam machine had been disassembled to permit accurate alignment of stagnation chambers with the two molecular beam axis. The machine has now been reassembled.

The chopper thiming signal electronics have been modified to increase speed and improve reliability. The light bulb has been replaced by an infrared LED, and the slow photodiode has been replaced with a much faster Motorola MRD 510. The risetime of the chopper signal is now about 15 nsec, a considerable improvement over the previous 2 μ sec rise-time. This will permit accurate time of flight analysis of the molecular beams and also of the scattered molecules. The molecular beam chopping disk currently consists of a 2" stainless steel disk with ten slots cut in it. The slots are about equal in width to the adjacent solid part of the disk, which means that time of flight data can be extracted only by examining the leading or trailing edge of the beam pulse as the beam is chopped. It is more desirable to have a narrow slot which produces a short beam pulse so that risetime measurements do not have to be made. The chopper wheel will be changed in the near future to include a slot comparable in size to the molecular beam width. The current chopper disk will be used until the preliminary detector evaluation studies have been finished.

The molecular beam detector is currently being evaluated. The detector consists of a Pierce gun ionizer which ionized the beam particles, lenses which focus the ions, and a particle multiplier to detect the ions. The Pierce gun is functioning properly, with the exception that the 1" long filament sags when it is heated. The filament must be positioned exactly correctly or it will touch the electron gun grid making the detector unuseable. When the present filament burns out, the filament holder will be replaced with one that allows the filament to be spring loaded (any failure which requires the opening of the ultra high vacuum section of the beam machine usually results in a delay of one day before the machine is ready to produce a beam, thus, reliability of parts is extremely important).

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A separate, already existing chamber (not connected to the beam machine) is being renovated and will be used to conduct tests on the detector, along with the addition of a quadrapole mass filter to the detector. This chamber has windows in it, and is already equipped with a QMS. The pump down time is much faster than for the beam machine, and it is thus hoped the beam machine can be used at the same time that modifications are being separately tested in the smaller test chamber.

It is believed that the current detector will be good enough to allow scattering data to be taken for some pairs of gases. It will be necessary, however, to make some changes to the detector if full use is to be made of the beam machine's capabilities.

VI. RADIO SCIENCES

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(VI. RADIO SCIENCES)

A. MODELING SUBSURFACE RESISTIVITIES WITH MAGNETOTELLURIC DATA (MT DATA) †

Professor H. W. Smith, Professor F. X. Bostick, Jr., J. E. Boehl, S. H. Cheng, and D. E. Wight

1. MAGNETOTELLURIC AND DIPOLE-DIPOLE SOUNDINGS IN NORTHERN WISCONSIN

This project, which has been concerned with the determination of the deep electrical conductivity structure of the earth's crust using dipole-dipole and magnetotelluric soundings, has been completed during the year. The techniques developed are considered to be significant to the investigation of the possibility of subsurface communication and to the site selection and antenna pattern determination for U.S. Navy Projects Sanguine and Seafarer.

This work has been reported at meetings and conferences, in one Masters Thesis, as part of the 1975-1976 Significant Accomplishments of the Electronics Research Center, and is currently being revised for publication in the Geophysical Monograph Series of the American Geophysical Union [1, 2, 3, 4].

2. A LAND TO SEAFLOOR ELECTROMAGNETIC PROPAGATION EXPERIMENT IN THE OLYMPIC PENINSULA

During the summer of 1976, scientists from Pacific Sierra Research Corporation, the above group from The University of Texas at Austin, and Scripps Institute of Oceanography performed an electromagnetic propagation experiment on the Olympic Peninsula in the northwest corner of the state of Washington. The main purpose of the experiment was to send ultra-low-frequency (0.1 to 10 Hz) signals from land to deep receivers (to 8,000 feet) on the seafloor. In addition, a number of sub-

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sidiary land-based measurements and magnetotelluric (MT) soundings were carried out. The operation of a grounded horizontal electric dipole transmitter as well as all land-based measurements was made by The University of Texas team. All sea-based measurements were made by a team headed by Professor C. S. Cox of The Scripps Institute of Oceanography and overall management of the project was the responsibility of Dr. E. C. Field and Mr. John Farquhar of Pacific Sierra Research Corporation.

Square-wave signals, using frequencies from 0.1 to 10 Hz and a peak moment of 1.6×10^5 amper-meters, were injected into the earth by the transmitter. Strong signals with a 20-30 dB signal to noise ratio for the fundamental were received on a 100 m long electrode pair emplaced on the seafloor at a depth of about 1,000 feet at a range of 22 km from the transmitter. It is concluded that these signals were from an over-down mode. However, measurements on the seafloor at ranges from 110 to 135 km at a depth of 8,000 feet using receiving antennas 540 m to 1,000 m in length failed to detect any signal. It is concluded that the ocean screened out the over-down mode and that any signal detected would have had to propagate through the crust. Calculations from these results indicate that a field would have been detected at 135 km and 8,000 feet depth if the effective conductivity of the propagation path were less than 3×10^{-3} mho/m. A report [4] on the land-to-seafloor portion of the project gives details of the measurements and conclusions.

The land-based measurements consisted of Magnetotelluric soundings at four sites and DC dipole-dipole resistivity soundings at fifteen sites ranging from about 4 km to the seaward side (northwest) to 120 km to the landward side (east and southeast) of the transmitting antenna. On the basis of the earth model indicated by the resistivity results from the two sets of measurements, it would appear the ULF electromagnetic signals could be propagated reasonably well in the lithosphere to distances in excess of 100 km along a path extending to the landward (east) of the transmitting antenna. These measurements also show a significant increase in the effective conductivity at depth at sites to the seaward side of the transmitter. This suggests that either the effective conductivity beneath the ocean is somewhat greater than that beneath the land sites, or that there is a conductive obstacle in the crust between the transmitter and the sea-based receivers. The latter possibility could be caused by the presence of a subduction zone, albeit inactive, near the present shore line. It is also a possible explanation for the negative

results at the longer ranges for the seafloor propagation experiment. These results are contained in a recent report [5] describing the land-based portion of the experiment.

3. DEVELOPMENT OF MAGNETOTELLURIC ANALYSIS AND INTERPRETATION METHODS

It has been recognized for some time that on-site, real-time analysis and interpretation of Magnetotelluric (MT) and Audio-Magnetotelluric(AMT) data is both a highly desirable and a reasonable goal. To be practical, however, the very large data accumulation and processing requirements of conventional methods must be simplified wherever possible. Substantial progress toward this goal has been made by a combination of hardware, in the case of the AMT system, and by the development of simplified analysis and inversion techniques. Two new techniques which have been used on an experimental basis are now fully operational and have been reported during this contract period.

The first is a simple, approximate method of MT analysis and inversion and is based on the asymptotic behavior of apparent resistivity curves at low frequency. It utilizes the fact that the asymptote for a single section of uniform resistivity over a perfectly conducting substrate depends only on the depth to the substrate, and is independent of the conductivity of the resistive section even if that conductivity is a function of depth. Also, the asymptote for the same resistive section over a perfectly insulating substrate depends only on the integral of the conductivity versus depth profile to the depth of the substrate. The simple method has been disclosed to a number of researchers who have used it successfully in a wide variety of situations. It has been presented at a conference and has been published in the Conference Proceedings [6].

The second technique uses the Hilbert Transform to incorporate phase as well as magnitude information in the final determination of the apparent resistivity versus frequency curve, and has greatly reduced the amount of experimental scatter which can often be excessive at noisy sites. The process has been termed "phase smoothing" and leads to what is essentially an unbiased estimate. The process has been presented at a conference and is to be included in an Appendix to the AGU Monograph paper cited in Section 1 above.

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Cambridge, MA 02139

Director, Stanford Electronics Laboratory
Stanford University
Stanford, CA 94305

Stanford Ginzton Laboratory
Stanford University
Stanford, CA 94305